TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

PERTTU KAIPIA

REDUCTION OF EMI COUPLING BETWEEN MOTOR AND GRID CONNECTIONS IN A TWO-LEVEL VOLTAGE SOURCE AC DRIVE

Master's Thesis

Examiner:
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ABSTRACT

PERTTU KAIPIA: Reduction of EMI coupling between motor and grid connections in a two-level voltage source AC drive
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Electromagnetic Compatibility (EMC) of a drive must be tested to make its use safe and disturbance free in an electric grid. The noise limits for drives are defined in the standard IEC 61800-03. The coupling between motor and grid cables in a conduit box of a drive bypasses the electromagnetic interference (EMI) filter and make it difficult to fulfil the standard. The goal of this study is to present design guidelines to reduce the coupling between connections with a cost effective way.

The first part of the study discusses the coupling between grid and motor connections theoretically. Based on the theory, the possible solutions for the problem are identified. The identified solutions are investigated with simulations and measurements with a simplified model of the drive connection environment. Assessment criterions are an effectiveness, a feasibility and a cost efficiency. The prototype drive is implemented with the best solutions and it is tested with standardized measurements. The investigated solutions were new placement of drive connections, shielding the drive connections and topology changes in an EMI filter.

The study presents that coupling between motor and grid connections of a drive has a significant impact to the amount of the conducted emissions to the grid. It also presents that proposed solutions reduce the coupling significantly. The most effective and still feasible proposed solutions were to shield the grid connection of the drive with an aluminium or a steel plate and increase the differential inductance in the grid connection. The conducted emissions of the prototype drive with the proposed solutions fulfils the C2 limit of the standard. The solution is estimated to reduce material costs of an EMI filter from 12 to 37 percent with an extra cost of the shield.

TIIVISTELMÄ

PERTTU KAIPIA: Sähkömagneettisten häiriöiden ylikuulumisen vähentäminen verkko- ja moottoriliitännän välillä kaksitasoisessa jännitevälipiirillisessä taajuus-muuttajassa
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Taajuusmuuttajan sähkömagneettinen yhteensopivuus (EMC) on varmistettava, jotta sen käyttö olisi turvallista ja häiriötöntä yleisessä sähköverkossa. Rajat taajuusmuuttajan tuottamille häiriöille on määritelty standardissa IEC 61800–03. Taajuusmuuttajan verkko- ja moottorikaapelien välinen ylikuuluminen laitteen kytkentätilassa ohittaa taajuusmuuttajan sähkömagneettisten häiriöiden (EMI) suodattimen ja vaikeuttaa edellä mainitun standardin täyttämistä. Työn tavoitteena on luoda suunnitteluohjeistus, jolla liitäntöjen välinen ylikuuluminen saadaan vaimennettua kustannustehokkaasti.

Tutkimuksen ensimmäinen osa käsittelee taajuusmuuttajan liitäntöjen välistä ylikuulumista teoreettisesti. Teorian perusteella tunnistetaan mahdollisia ratkaisuja ongelmaan. Tunnistettuja ratkaisuja tutkitaan tämän jälkeen simuloiden ja mittauksin yksinkertaisella mallilla taajuusmuuttajan liitäntäalueesta. Ratkaisuja arvioidaan tehokkuuden, toteuttavuuden ja kustannusvaikutusten perusteella. Parhaista ratkaisuista muodostetaan toimiva prototyyppi taajuusmuuttaja, jonka toimintaa testataan standardin IEC 61800–03 mukaisin mittauksin. Tutkitut ratkaisut ovat liitinten uudelleen sijoittelu, liitinalueen sähkömagneettinen suojaaminen ja EMI-suodattiminen topologian muutokset.

Työ osoittaa, että taajuusmuuttajan verkko- ja moottoriliitännän välinen ylikuuluminen vaikuttaa merkittävästi laitteesta verkkoon johtuvien häiriöiden määrään ja, että esitetyt ratkaisut vaimentavat tätä ylikuulumista merkittävästi. Tehokkaita ja helposti toteutettavia ratkaisuja ovat erityisesti verkkoliitännän suojaaminen teräs- tai alumiini levyllä ja differentiaalisen induktanssin kasvattaminen verkkoliitännässä. Työn lopputuloksena esitetyllä tavalla toteutetulla liitäntäalueella ja EMI-suodattimella varustettu taajuusmuuttaja läpäisee C2 tason johtuvien häiriöiden mittauksen. Tällä ratkaisulla saavutetaan arviolta 12–37 prosentin säästö EMI-suodattimen materiaalikuluissa ottaen huomioon sähkömagneettisen suojan aiheuttama lisäkulu.

PREFACE

These master's thesis were written at ABB Drives, in Drive Products business unit's electrical design team. I would like to thank ABB and my boss Jari Mäkilä for this opportunity. The working environment in Drives was encouraging, interesting and demanding enough.

M.Sc Ville Forsström was my instructor during thesis. Thank you for answers to my numerous questions and comments to my study. Thanks also for assistant professor Tuomas Messo from Department of Electrical Engineering at Tampere University of Technology who was my examiner.

Support from my closest relatives was also invaluable during this process.

Helsinki, 22.8.2018

Perttu Kaipia

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1. INTRODUCTION

Today’s grid connected electronic appliances need a disturbance free supply from the electric grid. This requires good quality from electricity generation and transmission but also that grid connected devices do not disturb each other. This topic is called electromagnetic compatibility (EMC). Like all grid connected devices a drive have to pass standardized EMC-tests before it can be sold on European markets. Because of the digitalization and the internet of things the number of sensitive electronic devices is increasing also in industrial environments where the drives are mostly used. This causes a need for drives that produce less Electromagnetic interference (EMI) to grid but are still cost effective to build.

It’s been noticed that coupling between a drive’s grid and motor connections may lead to a higher conducted EMI to grid. The coupling means that energy is transferred between coupled parts without a conductive path. In drive’s connections this means that EMI noise from the motor cable is transferred to the drive’s grid connection and further to grid because the EMI filter that is designed to prevent EMI noise flow to grid is bypassed this way. A widely used way to place grid and motor connections side by side is vulnerable to cause inductive coupling between each other because of the opened cable loops as presented in the figure 1.

Figure 1. *Easily couplable cables in a drive connection[1]*

An easy way to prevent coupling between connections would be to place connections to the opposite ends of the drive. However, to make assembly of the drive easy, the connections must be side by side. This is the main restriction in this study.

The goal of this study is to find out design guidelines to reduce conducted EMI by reducing the coupling between drive connections. The proposed solutions must be feasible and cost effective to implement in the different drive models. Also a possibility to use simulations to support design process is investigated. If the existing EMC performance is enough, the design instructions should reduce the number of the passive components used in the EMI filters and decrease the cost of the drive.

The objective of the first part of the study is to find out which solutions are proposed to similar problems before and to understand how EMI is generated and transferred in a drive. Based on these theories the different solutions to reduce EMI coupling are identified. These solutions are then simulated and tested with a simplified drive model and promising solutions are combined to the concepts that are tested with an existing drive. Also a feasibility and cost effect of the solutions is discussed.

The investigated solutions are divided to the three categories based on the solution type. These categories are the connector positioning solutions, the shield solutions and the EMI filter topology solutions. Each solutions are first separately discussed but final concepts combine the shield and the EMI filter topology solutions. The connector positioning solutions cannot be implemented to an existing drive.

To investigate only the effect of the EMI coupling in a drive’s connection environment, the simplified model of it is designed and used in simulations and measurements. The simplified model models drive’s connection cables and an EMI filter which were first identified to be main coupled components. Measurements with the drive system are used to validate the designed concepts. These measurements followed standardized EMC-tests.

EMI coupling is a common EMC-issue regardless of the application. Therefore this study applies widely general EMC research. Good practices are presented for example in Henry W. Ott’s and Clayton R. Pauls books Electromagnetic Compatibility Engineering and Introduction to Electromagnetic compatibility [2, 3]. Drive specific EMC research has been focused on EMC-filter and common-mode choke design or developing more EMC-friendly control design [4-7]. There were no previous study found about coupling between drive connections but the EMI coupling to filter components and simulation of it have been discussed[8, 9]. Coupling is based on capacitance and inductance which are presented in the Young & Freedman’s book University Physics [10].

2. THEORETICAL BACKGROUND

In order to reduce EMI noise in a drive it is important to understand how this noise is generated and propagated. Therefore a drive and its most important noise sources are discussed. To understand why reduction is important a concept of an electromagnetic compatibility and the most important EMC standards for drives are presented. An EMI filter is the already used device to reduce EMI noise. Therefore its effect to a coupling between grid and motor connections is introduced.

Mechanisms for EMI coupling are discussed in detail and a focus is on factors that increase or decrease the coupling. Shielding is a possible solution to reduce EMI noise and then it is useful to understand which aspects affect its effectiveness. Different shield materials are also discussed. Presented theories are applied in the part 4 where different solutions to reduce EMI coupling between motor and grid connections are designed and tested.

2.1 EMC in a drive

Electromagnetic compatibility (EMC) is one of the many things that have to be taken account in a drive design process. A good design makes sure that the drive is compatible with other devices and do not disturb the electric grid. It should also fulfil given standards. In this chapter the basic topology of a two-level voltage source ac drive is presented. EMC is discussed generally in a relevant extent to this study. The most important EMI sources of the drive is discussed in a detail and already used methods to reduce an EMI noise are identified.

2.1.1 Introduction to drives

A motor drive or a frequency converter is a device that is used to adjust the rotation of an electric motor. Widely used induction motors have their rotation speed directly proportional to the frequency of the supplying grid. A drive is connected between a supply grid and a motor and it varies the frequency that is fed to a motor. Most industrial drive applications are three-phase connected and only three-phase drives are discussed in this research.

A drive has three main parts in a circuit from an input to an output. The first element is a rectifier bridge that rectifies an AC-voltage to a DC-voltage. This rectified voltage is then stored to a DC-link which consist from electrolytic capacitors. The last stage is an IGBT (Insulated Gate Bipolar Transistor) -inverter which converts the DC-voltage to an AC-voltage with a desired frequency. This kind of topology is called a two-level voltage source drive. The two-level drive means that drive produces output voltage with two different possible phase outputs. Either positive or negative DC-voltage. Only two IGBTs per phase are needed in this case. A topology is presented in a figure 2.[11, 12]

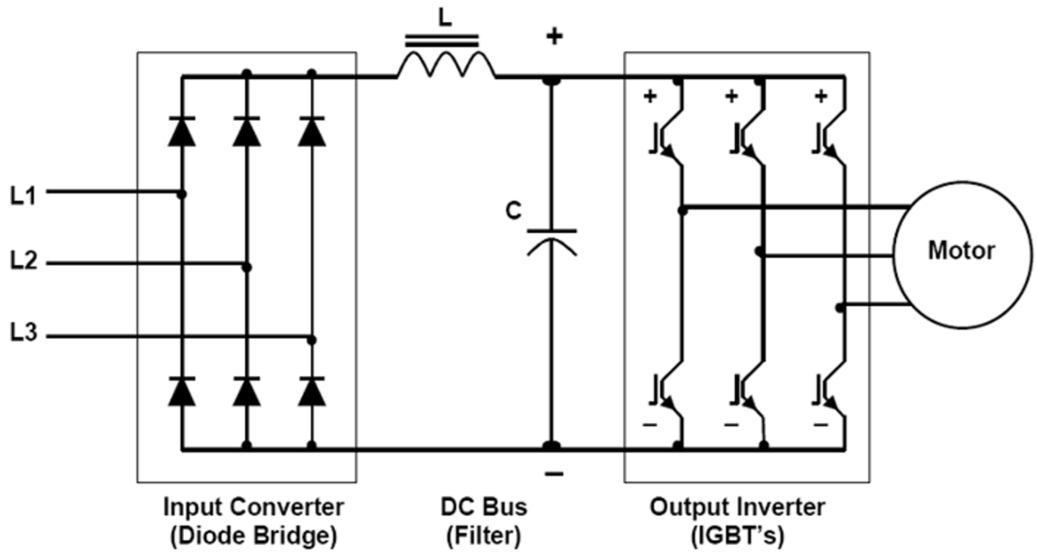

Figure 2. *Main circuit of a drive[11]*

A desired voltage is produced in a drive by switching IGBT-transistors. Transistors switching is controlled so that a high frequency square wave output signal has sinusoidal voltage with a desired frequency and amplitude as an average.[12]

Other components in a drive are control electronics, an internal power supply and EMC-filters. Control electronics measure and control the drive's main circuit and motor to sustain desired rotation speed and to detect possible malfunctions. The internal power supply produces the operating voltage to control electronics. EMC filters reduce EMI noise in a drive grid-connection to respond requirements in standards for grid-connected devices. This is discussed in more detail at the following sections.[13]

2.1.2 EMC generally

Electromagnetic compatibility (EMC) is a hypernym for all activities that make sure that electronic devices can work together without disturbing each other. This is achieved mainly by standards which define the limits how much external disturbance a device should endure and how much noise it may emit. In standards these attributes are called emissions and immunity. Qualification to standards is verified by official measurements. In this study only the conducted emissions are discussed.[13]

Emissions are called an electromagnetic interference (EMI). The EMI can be divided based on a propagation path to a conducted and a radiated EMI. The conducted EMI is an emission that couples via a conductive material. It flows in device's own conductors and grounded chassis. The conducted EMI is a potential problem for electric grids and devices connected to the same grid nearby. Therefore it is measured from a device's grid connection. The other propagation path is radiation. Radiated EMI noise is released away from the device as an electromagnetic far fields. This could interfere other devices further away. Radiated emission is measured with antennas. This study focuses on conducted emissions because coupling between grid and motor connections is a near-field phenomena and have only limited effect to the radiated noise.[2]

The standard IEC 61800-03 defines conducted EMI limits for drive systems at grid connections from 150 kHz to 30 MHz. The IEC standard have different noise limits for different applications. These limits are called C1, C2, C3 and C4. The C1 is the strictest limit and C4 is the most lax. Most drives pass at least C3 which is a standard for devices used in an industrial networks. The limit C2 is used when the device is used in a public network but installed by professionals. The trend is that customers require stricter limits and designs that fulfil the C1 are needed. The C1 is a limit for plug-in devices to the public network.[13] [14]

In a drive system conducted noise is normally divided based on its nature to a common-mode and a differential-mode noise. These noises and different solutions to reduce them are discussed separately at the following sections. However, in the standard conducted EMI measurement these two noises are not separated.[14]

2.1.3 Common-mode noise

Common-mode noise is a noise which occurs simultaneously in all three phases. It is caused by a common-mode current that is caused by a common-mode voltage. The common-mode noise is also called as a "ground-loop noise" because of the way how it is commonly detected. In an ideal operating condition there is no current from the three-phase system's star point to ground. However, the common-mode current flows that path.[4, 15]

Common-mode voltage is a root cause of common-mode noise. By the definition used in this study the common-mode voltage is a sum of all phase voltages divided by the number of the phases. Phase voltages are vector values and in a condition without the common-mode voltage the sum should be zero. The definition can be expressed as in the equation 1:

$$V_{cm} = \frac{v_a + v_b + v_c}{3} \qquad (1)$$

In a drive a common-mode voltage is mainly produced in switching events at the inverter. In a two-level inverter each phase is connected to a positive or a negative DC-voltage in each switching sequence. This means that there is always at least two phases connected to the same potential. In this case the produced common-mode voltage can be calculated following to the definition above. This is presented in the equation 2.[4]

$$V_{cm} = \frac{v_{dc} + v_{dc} - v_{dc}}{3} = \frac{v_{dc}}{3} \qquad (2)$$

The highest common-mode voltage is produced when all phases are connected to the same potential. In that case a common-mode voltage is same as a connected DC-voltage which is often the half of the voltage of the DC-capacitors. The common-mode voltages of the all switch combinations are presented in the table 1. The zero in the combination table means that the phase is connected to a negative voltage and the one marks the connection to a positive voltage.

Swicth com-bination			CM voltage
L1	L2	L3	
0	0	0	Vdc
1	0	0	-Vdc/3
1	1	0	Vdc/3
0	1	0	-Vdc/3
0	1	1	Vdc/3
0	0	1	-Vdc/3
1	0	1	Vdc/3
1	1	1	Vdc

Table 1. *The common mode voltages of the all switch combinations*

The common-mode voltage changes in every IGBT switching event with the switching frequency of a drive. It is often a few kilohertz. The investigated EMI noise is caused by the fast transients of this voltage and has therefore even higher frequencies. This kind of high frequency noise couples easily through capacitances [2].

When this common-mode voltage between an inverter and a ground potential finds a current path between these potentials it generates a common-mode current. A typical current path goes through parasitic capacitances from a motor cable and a stator winding to the ground. Then the current flows either via motor cable's PE wire or through grounded chassis back to a drive. A lower impedance route is selected. The loop is completed through a grounded neutral point of the drive's feeder transformer and then back to input phases.[5]

However, to reduce a common-mode current in a grid side of the drive it is common to connect a middle point of the DC-bus to a ground plate via capacitors. This topology reduces significantly a measured high frequency common-mode noise when the common-mode current flows through these capacitors instead of a feeder transformer. A drawback is that low frequency noise is increased. The grounded middle point of the DC capacitors is presented in the figure at the section 2.1.5.[16]

2.1.4 Differential mode noise

Differential mode noise is a noise that is measured as a difference between phases. The differential mode noise is normally a minor problem in drive systems compared to common-mode noise. In the drive systems it is impossible to completely separate an examination of common-mode and differential mode noise due to unsymmetrical and time-variant components such as a diode bridge and an IGBT.[6, 15]

Differential mode noise is caused when a high-frequency switching square wave current from an IGBT couples between phases. The worst case in a switching cycle is when one phase is connected to a different potential than two others. There a noise is coupled equally to two other phases and it flows back to a DC-bus through conducting IGBTs. Coupling between the phases after the IGBT occurs via parasitic capacitances in a motor cable and a motor. A circuit is closed at a DC-bus.[6, 7]

The described current loop above is completely inside a drive system and if it stays so it does not disturb the grid connection of a drive. The energy to this noise is taken from a DC- bus and hence this would require a stiff DC-bus which is not a case. Some of the power is always taken directly from the grid and therefore these voltage drops cause the noise to the grid connection. However, the magnitude of a differential mode noise is significantly lower than a common-mode noise.[7]

In some cases a measured differential mode noise could be caused by a common-mode noise. This occurs when the common-mode noise from a DC-bus is conducted to a grid via a diode bridge with similar mechanism than as described for the differential mode noise above. Phases where the noise is connected depends on the state of the diode bridge. There is always two phases connected to one potential and one to another in the DC-bus. When the noise is connected to only one or two phases it causes difference between phases that is measured as the differential mode noise.[15]

2.1.5 EMI filter

An ordinary EMI filter is a passive circuit that is placed to a drive’s grid connection. It consists of capacitors and inductors and the purpose is to provide a low impedance path to a ground potential for an EMI noise and the low impedance path to grid for a power. A noise is filtered from power based on a frequency and a distribution to a differential and a common-mode noise. A power signal frequency is 50 or 60 Hz and it is completely differential. The other signals are noise.

An important component to reduce common-mode noise is a common-mode choke. An ideal choke would have a high mutual inductance between phases and the lowest possible differential impedance. This way the common-mode noise sees a high impedance towards the grid when it is placed between a DC-bus and a grid connection. In theory it is based on the Lenz law. It says that a change in a current in an inductively connected inductor causes a similar but opposite current in the other inductor. Therefore when the inductors have mutual currents like a common-mode current, the both currents are cancelled. In practice the inductors of all phases of the grid-connection are coiled to a same core and the high mutual inductance is achieved that way.[17]

A frequency related impedance in capacitors and inductors is called a reactance. Mathematically the reactance is an imaginary part of the impedance and the resistance is a real part. A capacitor has a lower reactance X_C with a higher frequencies f as can be seen from the following equation 3:

$$X_c = -\frac{1}{2\pi f C} \qquad (3)$$

The C is a capacitance of the capacitor. The minus sign means a negative phase shift and that causes a voltage signal to be delayed related to a current. The inductor instead has a higher reactance X_L with higher frequencies f which is presented in the equation 4:

$$X_L = 2\pi f L \qquad (4)$$

The L is the inductance of the inductor. The phase shift of the inductor is positive and therefore a current is delayed related to a voltage signal.[17]

Differential noise filtering is based on a low-pass filter. In a second order low-pass filter there is a series connected inductor and a parallel connected capacitor to a ground potential. The inductor blocks a high frequency signal and the capacitor leads the noise to ground. The effectiveness of a filter can be increased by increasing the order of the filter. A cost-effective way to do this is to use dc-bus capacitors and a leakage inductance of the common mode filter. When a second order filter is placed after a DC choke, a noise from an inverter sees first the dc-bus capacitors, then a DC choke and then a second order filter. This topology represent a third order filter and it is presented in the figure 3.

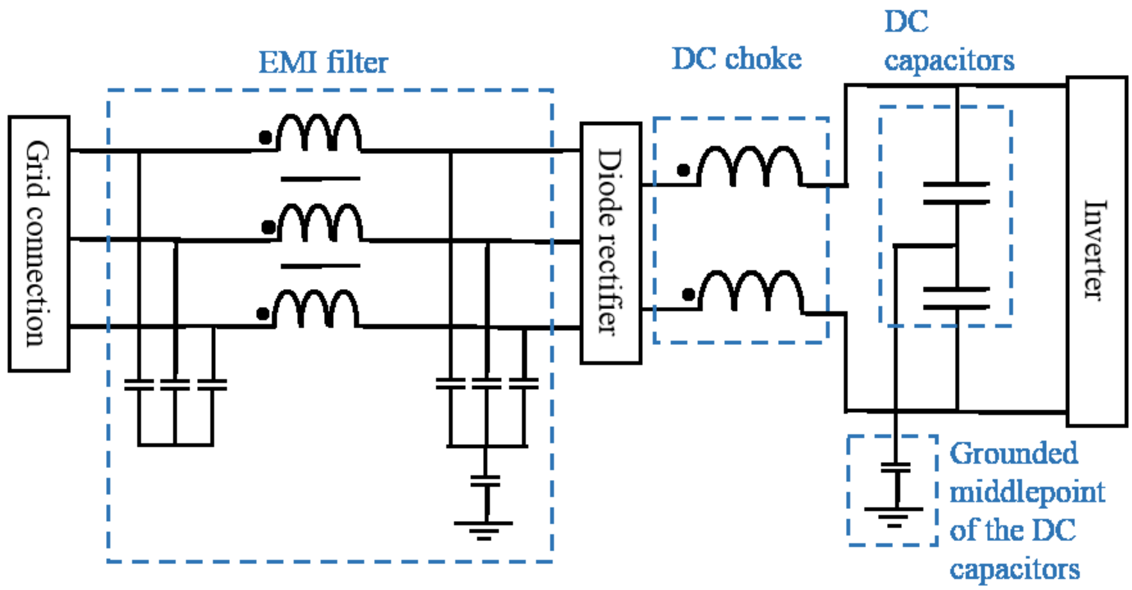

Figure 3. *Ordinary EMI-filter topology of a drive*

The inductance which affects to a differential noise in the common-mode choke of the filter is the leakage inductance. It is caused by the leakage flux and with ferrite cores it is approximately 1 percent of the common-mode inductance.[17]

2.2 EMI coupling in a drive

EMI coupling is an unwanted coupling of an EMI noise to a victim circuit. In a drive this means that the EMI noise generated by the IGBT's is coupled to a grid connection and seen in the EMC measurements of conducted emissions. There are two possible mechanisms for EMI noise coupling: capacitive and inductive coupling. Both of the mechanisms and problems they cause are discussed in the following sections. Also the effect of the EMI filter is discussed.

2.2.1 Capacitive coupling

Capacitive coupling means a coupling where an energy from one circuit is transferred to another through an electric field. It is also called an electric field coupling. Capacitor that connects circuits can be either an individual component or a parasitic capacitance of another component. For an EMI in a drive system the most important capacitive couplings are the couplings in a motor cable, between an IGBT and a heatsink and between traces on a printed circuit board.[18]

There is a capacitance between all conductors placed close to each other. The capacitance tells how much charge is stored in an electric field as a ratio of an electric potential. The more the charge is stored the stronger the electric field is between the conductors. This means that higher capacitance allows more charge to flow though it and makes it possible to lead more current. In a drive these parasitic capacitances allow more routes for an EMI noise and make it more difficult to suppress.[2]

The amount of a capacitance depends mainly on three factors. The distance between conductors, the material between the conductors and the size of the common area that the conductors have with one on the other. The capacitance of a simple parallel-plate capacitor is defined as followed in the equation 5:

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} \qquad (5)$$

There ε_r is a relative permittivity of the material between plates. ε_0 is the permittivity of the vacuum. Also known as the electric constant. A is the common area of the plates and d is the distance between those. As we can see the dielectric strength of the material and area between plates are directly proportional to the capacitance and increasing a distance between the plates decreases the capacitance.[10]

High capacitance itself does not automatically mean a high noise current though it. The amount of the current is defined by an impedance of the capacitor. The part of the impedance caused by capacitor is called reactance. It is inversely proportional to frequency and the equation 6 for it is presented:

$$X_c = -\frac{1}{2\pi f C} \qquad (6)$$

Here it is seen that higher frequency noise sees a lower impedance path and therefore even a small parasitic capacitance could effectively conduct a high-frequency EMI noise.[10]

Capacitive coupling in a drive occurs in a motor cable, in a parasitic capacitances of the motor and between traces in a printed circuit board. This makes it a major coupling mechanism for EMI noise propagation between the motor and the drive. It is also intentionally used to lead high frequency EMI noise to a ground potential in an EMI filter.[13]

It can be assumed based on the theory of the capacitive coupling that its effect to the coupling between the drive connections is negligible. The distance between the connectors and connected cables is too high and a common area is too small to cause the notable capacitive coupling. For example the simulated capacitance between grid and motor connections in investigated device was 0,12 pF. The coupling between connections should therefore be inductive.

2.2.2 Inductive coupling

Inductive coupling occurs through a magnetic field. There a current of a conductor causes a magnetic field which induces a current to another conductor nearby. The magnitude of this coupling is represented with a mutual inductance or a coupling coefficient. The mutual inductance depends on self-inductances of the coupled circuits and the medium and a geometry between them. In a drive this is mainly a parasitic phenomenon.

Inductive coupling and inductance is explained with two of the Maxwell's equations. The Ampere's law declares that a moving charge causes a magnetic flux and the Faraday's law of induction presents how a changing flux through a conductive loop causes an electromagnetic force.

Inductance is a quantity that describe a component's or circuit's ability to resist a change in a current. The changing current in a circuit causes a magnetic flux based on Ampere's law and that induces the opposite electromagnetic force to circuit itself according to the Faraday's law of induction. The simplified Faraday's law of induction is presented in the equation 7:

$$\varepsilon = -\frac{d\Phi_B}{dt} \qquad (7)$$

A changing flux Φ_B through a conductive loop causes an electromagnetic force ε. The minus sign in front of the equation comes from the Lenz's law and means that the induced current flows to opposite direction than the original current. This supresses a change of the current.[2, 10, 17]

The inductance that a component causes to itself is called a self-inductance. The higher inductance causes the higher suppression but also a higher flux. The inductance could be measured either based on the flux (8.1) or based on the induced electromagnetic force (8.2). The Φ_T is the total flux in the inductive component and dI/dt is a change in a current. Equations presented follow:

$$L = \frac{\Phi_T}{I} \qquad (8.1)$$

$$L = \frac{\varepsilon}{dI/dt} \qquad (8.2)$$

When the second equation is solved for the electromagnetic force in the equation 9, it is seen that the high inductance leads also to a higher induced electromagnetic force.

$$\varepsilon = L\frac{dI}{dT} \qquad (9)$$

Here it does not matter if the flux is produced by another inductance. Because the self-inductance describes a circuit's ability to produce the flux but also a sensitiveness to induce the flux caused by other circuits, an inductive coupling between two circuits depends from their both self-inductances.

The mutual inductance describes how much electromagnetic force, a current in one circuit induces to the other circuit. Mutual inductance M between circuits 1 and 2 can be represented as in the equation 10 [2]:

$$M_{12} = \frac{\Phi_{12}}{I_1} \qquad (10)$$

The Φ_{12} is the flux in the circuit 2 caused by the circuit 1. If the circuits are perfectly coupled the mutual inductance depends only on the self-inductances and can be calculated as in the equation 11:

$$M = \sqrt{L_1 L_2} \qquad (11)$$

However, a perfect coupling is achieved only for loops that are inside each other. To describe a strength of the inductive coupling a coupling coefficient is often used. Coupling coefficient k represent how much of the maximum coupling is realised. It can be calculated as a ratio between the actual and the perfectly coupled mutual inductance. This is presented in the equation 12:

$$k = \frac{M}{\sqrt{L_1 L_2}} \qquad (12)$$

The coupling coefficient is an easy way to compare the inductive coupling between different scenarios.[2]

Geometry of the circuit and the media around it are the main variables for a self-inductance. A mathematical inductance calculations are based on the Maxwell's equations. A different geometries have been calculated through and the inductance of a loop is for example presented in the equation 13:

$$L = \mu\mu_0 \left(\frac{D}{2}\right) \cdot \left(ln\left(\frac{8D}{d}\right) - 2\right) \qquad (13)$$

Where μ_0 is the permeability of vacuum, μ is a relative permeability of a loop core, D is the diameter of a loop and d is a dimeter of a wire. Here it is seen that a larger loop area increases the self-inductance. A relative permeability in an equation presents that a high permeability material core inside a loop allows higher flux density inside a loop and causes higher inductance. These principles hold true with the all geometries.[2]

The mutual inductance depends on a self-inductances of an inductively coupled circuits but also on a distance and orientation between the coupled circuits. The Biot-Savart law for straight conductors presents that the flux density B around the conductor is directly proportional to the magnitude of the current I and inversely proportional to a distance from the conductor r. The Biot-Savart law for the infinitely long and straight conductors is presented in the equation 14:

$$B = \frac{\mu_0 I}{2\pi r} \qquad (14)$$

Where the μ_0 is the permeability of vacuum. The Biot-Savart law is derived from the Ampere's law.[2]

The effect of an orientation between coupled circuits is seen from an integral version of the Faraday's law of induction presented in the equation 15:

$$\oint_{\partial S} E \cdot dl = -\frac{\partial}{\partial t}\int_S \; B \cdot n \, da \quad \forall S \qquad (15)$$

An induced electric field E is calculated as a path integral via path l and it is a dot product between changes in a flux B and the normal n between the flux and the electric field directions. The dot product goes to zero when its elements are parallel so a mutual induction decreases when coupled circuits are more parallel.[17]

Motor and grid connectors are side by side at the same level in a drive. Each phase of the input and output cables are connected to connectors with separate wire. This forms a wire loops inside a conduit box as presented in the assembly instructions of the drive in the figure 4. The loops are marked with red boxes.

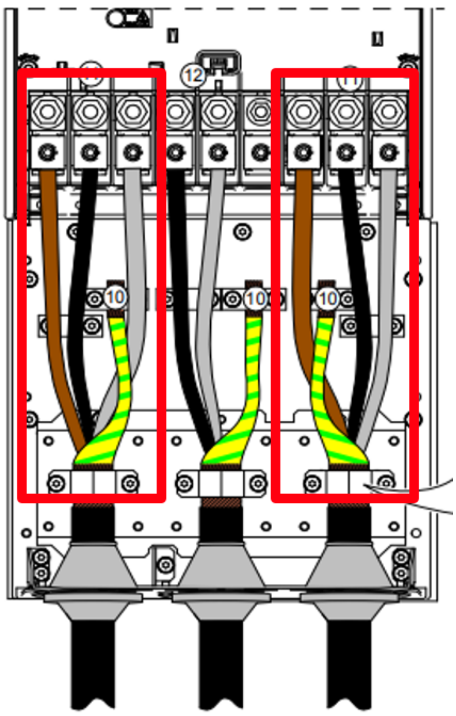

Figure 4. *Assembly instructions for input and output cables[19]*

This kind of structure is vulnerable for inductive coupling based on the presented theory. It was also noticed in the EMC measurements of the conducted EMI that placing the grid cable away from the motor cable reduces conducted emissions from 10 to 20 dBuV. Solutions to reduce this coupling is presented in part four.

2.2.3 Effect of the EMI filter

The EMI filter is normally connected to the grid connection of a drive as presented in the section 2.1.5. Therefore it has a major effect to an impedance of a loop where a magnetic interference from a motor cable is coupled. The high impedance in the loop reduces the coupled interference. There is the two possible loops in the grid connection. The first one is a common-mode loop and the second is a differential mode loop. The EMI filter should be designed to minimise coupling to both loops.

Common-mode loop forms between a phase conductors and a ground plate connected with grounding capacitors of the EMI filter and a grounding point of a feeder transformer. This is presented at the figure 5.

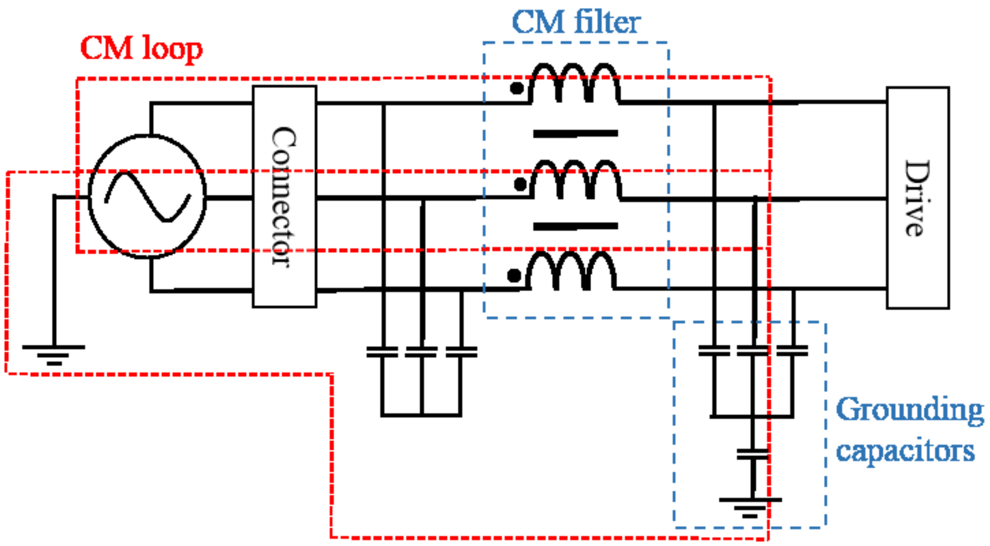

Figure 5. *A common-mode loop in a grid connection*

In the ordinary EMI filter the common-mode path for coupled interference goes through the common-mode filter. Its high common-mode inductance effectively prevents the coupling to common-mode loop. X-capacitors at the grid side of the common-mode filter should not be grounded to maintain this high common mode impedance.

The second option is a differential loop between phase conductors. The one end of this loop is connected in a feeder transformer and the other by x-capacitors of an EMI filter. This is presented at the figure 6.

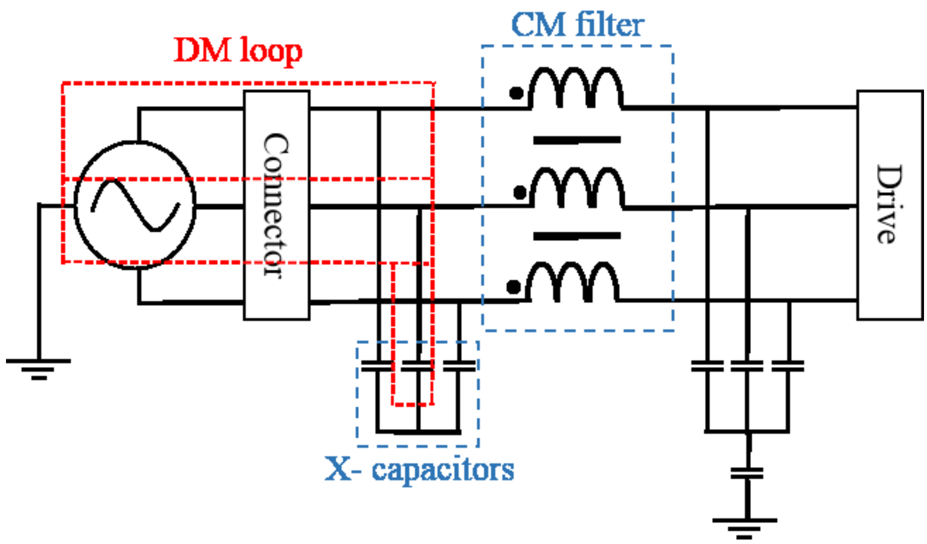

Figure 6. A differential loop in a grid connection

As seen in the picture, there is no differential impedance at the loop and a coupled interference can easily flow to grid. Adding a differential inductance to phases may reduce this. It can be done for example by placing another common-mode filter to the grid side of the grounding capacitor due to its leakage inductance. Removing the capacitors could be an option if a benefit of the reduced coupling is bigger than the decrease in filter performance due to lower order of the differential mode filter. If the leakage inductance of the common mode filter is low, removing the grid side capacitors do not have an effect because the differential loop is formed through X-capacitors at the drive side of the filter.

The other option may be to minimize the coupling by minimizing the differential loop by the placement of the x-capacitors. Placing the capacitors away from the grid connector forms a large loop which is sensitive to a magnetic interference. Therefore the capacitors should be placed next to grid connector.

The magnetic interference from a motor cable couples also straight to an EMI filter. The placement of the filter relative to the motor connection and possible shielding of it may therefore affect the coupling between the grid and motor connections. Different solutions are presented at the chapter 4.4.

2.3 EMC-shielding

EMC-shielding means protecting EMI-sensitive parts of the electric circuit with a protective material structure. Ordinary shields are made from metals. The shield could be placed either next to an EMI noise source or next to the sensitive circuit. There it should prevent the coupling through an electromagnetic field. In this study the possibility to protect a grid connection of a drive is discussed. A different shielding techniques are presented in the section 2.3.1 and literature review about different shield materials is presented in the section 2.3.2.

2.3.1 Shielding techniques

Shielding techniques are different depending on which kind of an EMI noise field is shielded. The electromagnetic field can be either a near or a far field and the near field can be predominantly an electric or a magnetic. This depends on an EMI noise source and a victim circuit's distance to it. When the noise source and the victim circuit are closer than 1/6 of the noise wavelength the EMI field is called the near field. In an ordinary drive the distance between grid and motor connections is a few centimetres. However, the wavelength of the 150 kHz to 30 MHz EMI noise is over ten meters so it is the near field noise.[2]

Predominance of a near field between an electric field E and a magnetic field H is defined between their ratios. This ratio is called the wave impedance. Characteristic wave impedance of the far field in a free space is 377 Ω. Because the magnetic and the electric fields change is not constant in a near field distances the impedance should be higher or lower than that. Therefore if the ratio E/H is under 377 the field is predominantly magnetic and otherwise it is electric. In other words if the noise source has a high voltage and low current the electric field dominates. In an opposite case the noise is predominantly magnetic. In a drive's motor cable the EMI noise has a high current and a low voltage so it is predominantly magnetic.[2]

Shielding a victim circuit for a predominantly magnetic near field can be based on four different physical phenomenon. These are an absorption loss, reflection loss, an eddy-current cancellation and diverting magnetic fields with magnetic materials. Used techniques are chosen based on the frequency of the noise and physical constrains of the shielded device. Geometry and a material of a shield should be optimised for each technique.[2, 3]

In a shield that is based on the absorption loss, the EMI noise field is absorbed into heat. This happens when magnetic field induces currents to a shield and these resistance of the material turns currents to heat. The absorption loss A for the shield plate can be calculated as follows in the equation 16:

$$A = 3{,}34t\sqrt{f\mu_r\sigma_r}\ dB \qquad (16)$$

Where the t is shield's thickness, μ_r is the relative permeability of the shield material and σ_r is the relative conductivity of the shield material. The f is the frequency of the magnetic interference. As can be seen, the absorption loss can be maximized by thickest possible shield and with a high permeability and conductivity material. Absorption loss is the most important phenomenon to maximize in a shield of a drive connection. It is highly effective with the conducted emissions frequency range compared to the other techniques presented later in this section.[2, 3]

Reflection loss is more effective with electric fields but it still has a role with magnetic fields. It means a loss that occurs when a part of the field's energy is reflected from the interface between high and low impedance mediums. The electric field is reflected when impedance of the medium decreases and the magnetic field is reflected when impedance rises. This kind of interfaces occurs when a shield is conductive and the medium around it is an insulator like air. The reflection loss R to magnetic fields is presented in the equation 17:

$$R = 14{,}6 + 10log\left(\frac{fr^2\sigma_r}{\mu_r}\right)\ dB \qquad (17)$$

Where the f is a frequency of the magnetic interference, the r is the shield's distance to a noise source, the σ_r is the relative conductivity and the μ_r is the relative permeability. The reflection loss is proportional to the frequency of the noise and to the distance to the noise source. Therefore the magnetic reflection loss can assumed to zero with the near field distances which makes this phenomenon impractical in the investigated situation.[3]

Eddy current cancellation means a situation when a magnetic interference induces eddy currents in a shield and these create a cancelling magnetic field according to the Lenz's law. In a perfectly conducting material the sum of these fields is zero. The problem with this technique is that it needs the constant eddy currents but a high absorption loss with higher frequencies is reducing those. This causes that cancelling magnetic fields are not formed. If this technique is used, the absorption loss needs to be minimized. This can be done by implementing the shield as a single wire loop which is placed over the EMI source. When a magnetic field goes through a loop a current is induced to it. This current creates a cancelling magnetic field which reduces the interference. In that case there is no eddy currents and therefore electrical losses are minor. This technique is also called as a "shorted turn method" [3, 20]

Magnetic materials can be used to reroute a magnetic interference to pass a sensitive circuit. When a magnetic field meets the magnetic material it starts to follow it because of it's lower reluctance. This can be exploited in shielding by implementing a shield around the sensitive circuit. The magnetic interference flows then trough the shield and not through the sensitive circuit. This technique requires a complete closure around protected circuit and does not work with a single plate. Idea is presented in the figure 7.[20]

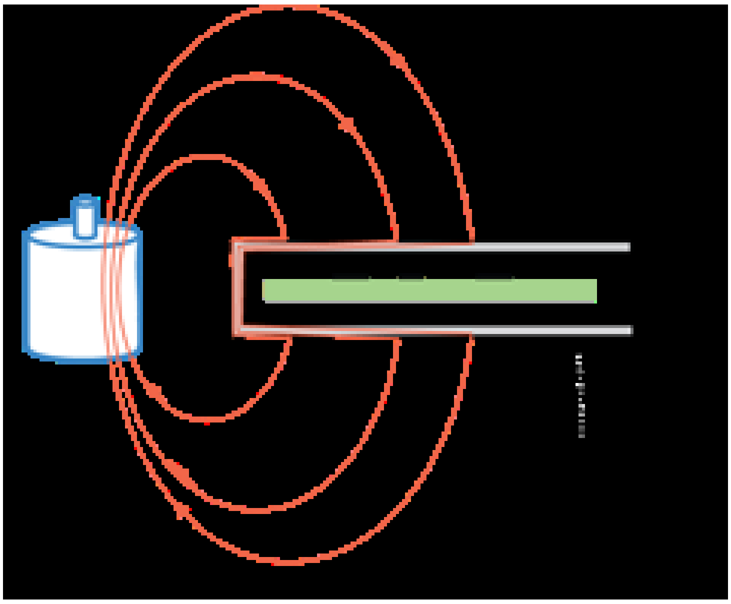

Figure 7. *The shield using magnetic materials [20]*

Material is said to be magnetic when it has a high permeability. The permeability measures material's ability to amplify a magnetic field inside itself and it depends on a frequency and a magnetic field strength. The permeability is higher with a lower frequencies and lower magnetic field strengths. If a dc permeability of the material is high the permeability decreases faster as a function of the frequency and the magnetic field strength than if the dc permeability had been lower. This means that almost all magnetic materials have a same permeability after 20-100 kHz and therefore the special materials are useful only with low frequencies. The special materials are also expensive which makes those impractical to be used in a mass produced drive. The high magnetic field strength can saturate the high permeability material also at the low frequencies and if these materials are used the saturation should be avoided. If the magnetic field strength is too high the shield can be designed with two materials. The first layer is made from a low permeability material and that reduces the magnetic field strength so that it does not saturate the high permeability material at the second layer. The two material shields are also an expensive solution.[2, 3]

The shield geometry is designed to maximize a shielding effect. In generally a shield should be designed so that all magnetic interference from a source to a victim circuit goes through the shield and not around it. In an optimal situation the shield is a closed box which is placed over either the source or the victim. In many cases that is not feasible and different apertures need to be designed. The most important properties for the aperture are the biggest linear dimension and a shape of an edge of the aperture. Seams and joints have an effect to a shielding effectiveness but those are not discussed because only individual shields are needed.[2, 3]

An aperture affects to the induced currents flowing in a shield. The currents need to bypass the aperture and this disturb a cancelling magnetic field they could create and decreases the shielding. The bigger linear dimension of the aperture detours more of the currents. The area of the aperture is not important. This is presented in the figure 8. Picture A presents a current flow in intact surface and the pictures B to D presents affected current flow in the pierced surface.

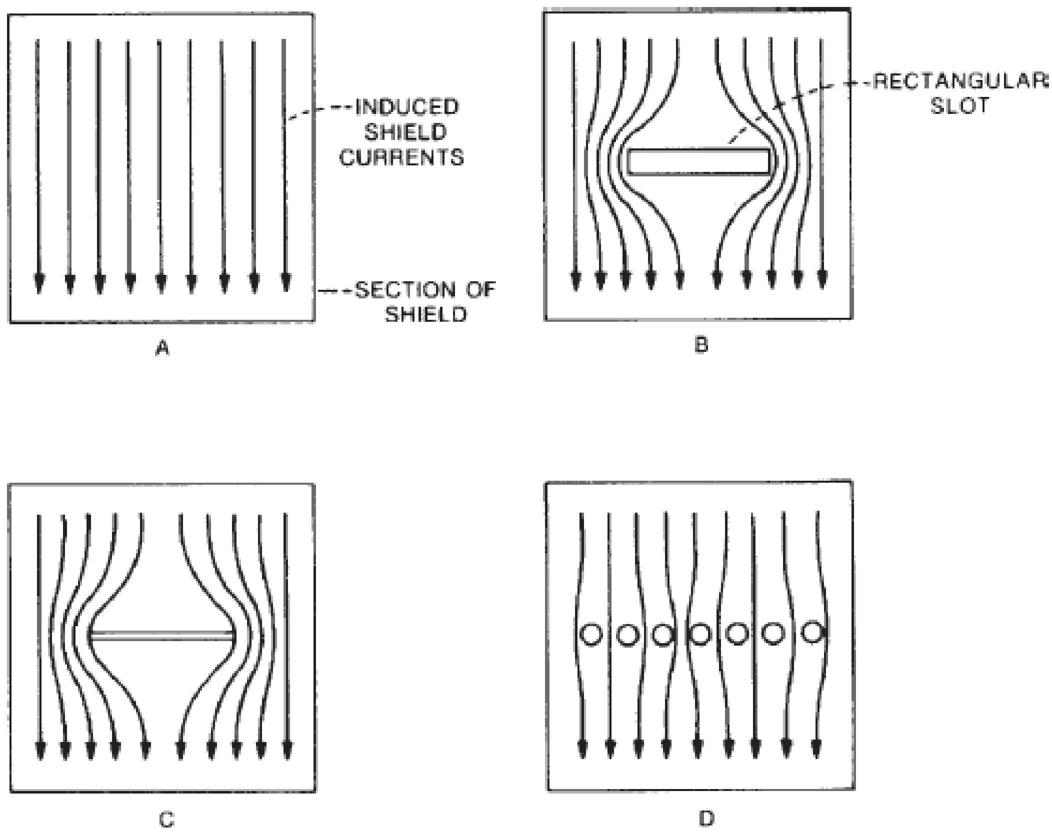

Figure 8. *Effect of shield discontinuity on magnetically induced shield currents[2]*

As can be seen from the figure that the option D has the largest area but smallest diversion to the currents. In the pictures B and C the current is significantly packed which weakens the cancelling magnetic field it cause. Circular shapes reduces the maximum linear dimension of the aperture and therefore those should be preferred.[2, 3]

Magnetic interference passing shield through an aperture depends on a wavelength of the interference and its ratio to the maximum dimension of the aperture. This passing can be decreased with higher edges of the aperture. These are called as “waveguides”. The apertures that are smaller than 1/10 of the wavelength do not effectively propagate a magnetic field. In this study the highest investigated frequency is 30 MHz which 1/10 wavelength is 99,3 cm which is significantly more than the possible apertures in investigated shields. Therefore the magnetic field do not leak through these apertures and waveguides are not needed.

Effectiveness of a shield S can be defined as a difference in a magnetic field strength before and after the shield. This difference is presented as a decibels. The equation 18 for this is presented:

$$S = 20log\frac{H_0}{H_1}\ dB \qquad (18)$$

Where the H_0 is a magnetic field strength before the shield and H_1 after it [2]. Measuring a magnetic field strength is difficult and therefore the quantity which is more used in the EMI filter design called insertion loss is used in this study. Insertion loss IL is a relative difference in the output power of the system without of the tested circuit (P_1) compared to the power of the system with tested circuit (P_2). It is defined as decibels as presented in the equation 19:

$$IL = 10log\left(\frac{P_1}{P_2}\right)\ dB \qquad (19)$$

Insertion loss is used also to measure effectiveness of the other solutions than shielding to make comparing possible.

2.3.2 Shield materials

The most important parameters of a shield material are relative permeability and conductivity. The difference in these can increase or decrease the shielding effectiveness of the different techniques as presented in the previous section. Other interesting parameters are density, cost, and corrosion sustainability. These measures the feasibility of the material to the drive use. A relevant parameters for the different materials are presented in the table 2. All presented materials are corrosion sustainable except a silver.

Table 2. The possible shield materials and their parameters[21, 22]

Material	**σ_r**	**μ_r**	**density (kg/m^3)**
Silver	1,05	1	10490
Copper	1	1	8940
Gold	0,7	1	19320
Aluminium	0,61	1	2712
Brass	0,26	1	8400
Bronze	0,18	1	7700
Tin	0,15	1	7220
Lead	0,08	1	11340
Nickel	0,2	100	8908
Stainless steel	0,02	500	7500
Mumetal (at 1 kHz)	0,03	20 000	8740
Supermalloy (at 1 kHz)	0,03	100 000	~9000

It can be seen from the table that most of the ordinary conductive materials such copper have a low permeability. Therefore those produce only a reflection and an absorption losses as a shield. As said before, the absorption loss is the most effective at investigated frequencies and therefore an aluminium would be a good material because of its low density. The benefits of the stainless steel are a significantly higher permeability than copper or aluminium and good availability. The permeability can make a shield more effective at the lower investigated frequencies. The special magnetic materials are not better than steel after 100 kHz as can be seen in the figure 9.

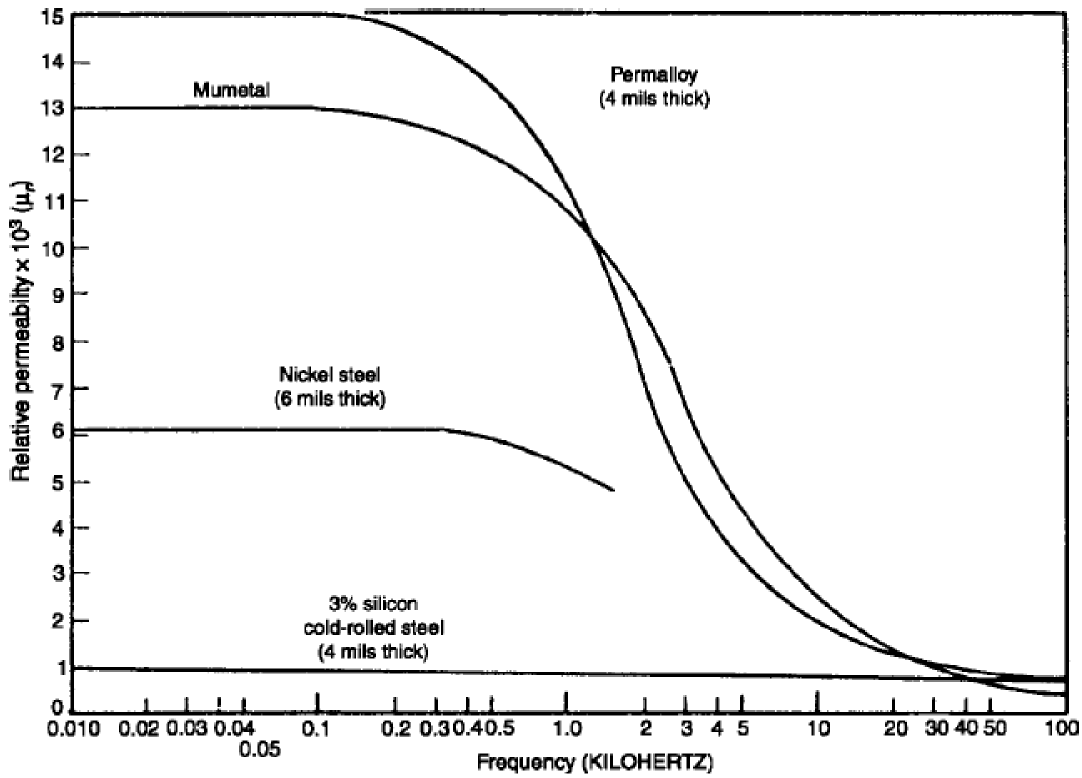

Figure 9. *The relative permeability of shield materials as a function of a frequency[3]*

Based on theory the proposed materials for the shield are aluminium and stainless steel. The both have a good conductivity which produces absorption loss especially aluminium. The steel has also some permeability which can be effective at lower frequencies. However, the absorption loss is more important. Both materials are relative cheap and corrosion sustainable which makes them feasible to be used in the mass produced industrial device.

3. RESEARCH METHODS

This study was implemented by combining simulations and real life measurements. The simulations were used to test efficiently several theory based solutions. Validity of the simulations were proven by the measurements. Reliability and validity of the methods is also discussed in this part.

A simplified model of the drive connector system including an EMI filter was designed and built. This reduces parasitic phenomenon that occurs in a full drive system and makes it possible to research different solutions separately. A simulation model of the simplified model was created to match with a measurements.

Measurements with a full drive system were carried out to validate a proposed solution for existing drive. These measurements followed conducted emissions test of the standard 61800-03.

3.1 Simplified measurement model

In a drive there is many parts that radiate EMI noise or have an effect to its propagation. In this study only a noise coupling between a motor cable and a grid connection was researched. Therefore a measurement model which has only parts that effect to that phenomenon was built. Simplified measurement model is a simplified structure of a drive connector environment and it models the motor and grid cables and an EMI filter. The coupling from a motor cable to a grid cable and the EMI filter and different solutions to reduce the coupling have to be able to be measured. The physical model should also be easy to model in a simulator software and connect to a spectrum analyser.

A size of the measurement model was decided to be 1:1 to a drive that had problems with an EMI coupling. In the grid side there is three phase conductors but a motor cable is represented as a one EMI loop to make measurements more straightforward. The length of the conductors is the same as the distance from a cable clamp in a conduit box to a drive connectors. The dimensions of the simplified system are presented at the appendix A. The simplified measurement model is presented in the figure 10.

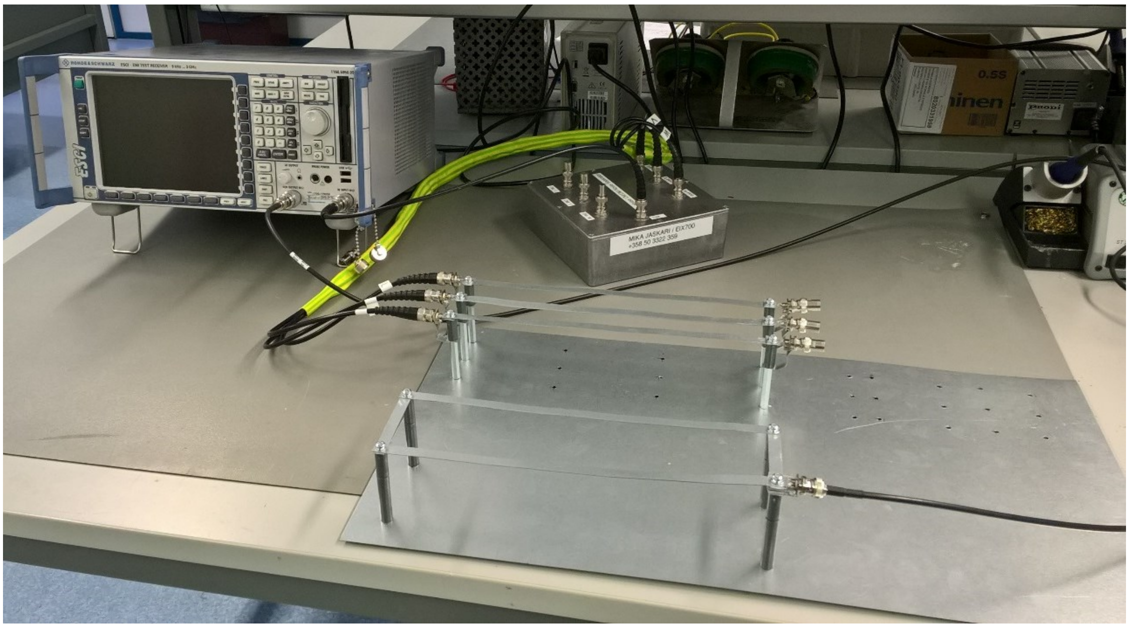

Figure 10. The simplified measurement model

The conductors are placed on insulated pillars and can be moved in either horizontal or vertical direction. In vertical direction it is achieved by moving the pillars to a new position. Horizontal movement is implemented by stacking one pillar on another. The whole model is created on the large ground plate and possible groundings are made straight to the plate. Different shields can also be assembled on the plate.

An EMI filter topology is variable and consist of three packages of grounding capacitors and two pairs of ferrite rings. Different ferrite materials and capacitor values can be used. Each part of the filter can be replaced by conductor. The EMI filter is built on the separate plate to make it possible to use separately in the future.

The connection to a measurement device and to an EMI generator is implemented with BNC-connectors that are soldered between phase conductors and grounding pillars. Non-measured connectors can then easily be terminated to ground with a 50 ohm terminator.

3.2 Simulation

Simulations are an emerging tool to analyse an EMC issues in an electronic design. Computational power of the computers and simulator software are developing rapidly and it makes possible to simulate more complicated systems. Simulation is a quick way to test an effect of the changes in a design. It is also more cost efficient than building prototypes. In this study an inductive coupling between grid and motor cables is simulated with a simplified model of the drive connector environment and with a full drive system.

Basic concept of these simulations were to model mutual impedances of conductive structures with suitable 3D simulation tool and then export results to a circuit simulator where passive components can easily be added. A parasitic behaviour is modelled as series of ideal components. These parasitic values were determined based on an impedance analyser measurements.

3.2.1 Simulation software

This study was conducted for ABB and the company offered also simulator software. The company was already using ANSYS Q3D, Simetrix and MATLAB software for the EMC design. The Q3D models resistances, capacitance and inductances of the given 3D conductive structures. These results are exported to Simetrix circuit simulation software and post processing of these results is done with MATLAB.

It was known that Q3D can reliably model conductive structures at the desired frequency range from 2 kHz to 30 MHz as it was already used to EMC simulations. The Q3D is a method of moment's simulator and uses adaptive meshing [23]. It means that software divides objects to a small regular pieces and calculates electromagnetic properties to those based on the Maxwell's equations. The size of the pieces is relative to the complexity of the modelled objects. Software calculates results again until user defined accuracy is achieved.

Results of all pieces in a same net are summed together. The net is a solid conductive structure. The final results are presented between user defined ports which are points where the nets are connected or a component is placed. The results are presented as a matrix between user defined ports.

However, there is some simplifications in the software. Q3D models only a surface of the object. It is also quasi-static solver and does not calculate a time dependence part of the Maxwell's equations like eddy-currents. It present results as an impedance matrix (RLGC-parameters) which are easy to integrate with a system level simulator. These values are also easy to understand when investigating parasitic phenomena compared to more precise software that present s-parameters like ANSYS HFSS and CST Microwave Studio.[23]

A problem with the Q3D was its unsure ability to model shielding which was not tested before and was expected to be poor because only a surface of an object is modelled. However, in a short example simulation there was a notable shielding effect and its validity were decided to be tested in this study.

Simetrix is a common spice model circuit simulator. It is a tool where a system level simulation is done. There exported equivalent circuits are connected with ideal components and connectors. Different excitations can be defined and results can easily be post-processed. Post processing was done with MATLAB. The insertion loss for each phase was calculated compared to a reference situation over an investigated frequency range.

3.2.2 Simulation model of the simplified measurement model

The designed simplified model of a drive connector environment is presented at the chapter 3.1. The designed model was modelled in simulation software and different solutions to reduce inductive coupling were simulated. These solutions are presented in the part 4. The 3D model of the simplified systems conductive structures were created with Q3D and passive components were modelled with an impedance analyser. The spice model of the design were then exported to Simetrix where circuit level simulations were done.

The first step in building a simulation is to create a 3D model of the simulated system. The simplified model were designed with Q3D software so the 3D model already exists. The modelled measurement system is presented in the figure 11.

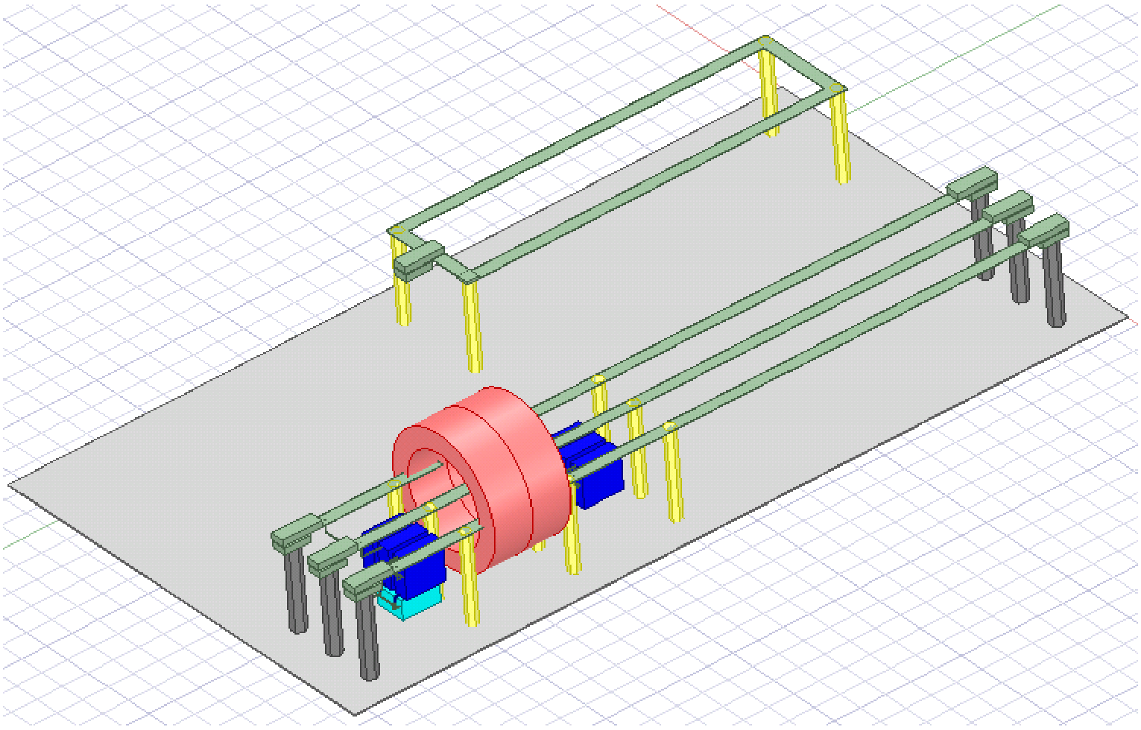

Figure 11. *The Q3D model of the designed measurement system*

The loop conductor on the upper right corner represents a motor cable. A grid side is on the right and a drive is on the left. Then simulation ports and nets were needed to be defined. The ports were placed to all places were a component need to be placed and to connectors. Ferrite rings were defined as non-model objects and were modelled to circuit level simulation as presented later.

Film capacitors magnetic behaviour were modelled to Q3D with conductive rectangular. The rectangular has the same size than modelled capacitor without dielectric cover. This models EMI coupling straight to the capacitors. The more precise modelling of the film structures does not improve accuracy of the simulation [8].

A simulation setup were defined to solve inductive RL-matrix and capacitive GC-matrix. Desired solution frequency was 20 Mhz. Results were exported as a spice equivalent circuit. The results included both RL and CG matrixes. An acceptable error was one percent. This means that software calculates simulation again with a more precise partition until the results chance are under one percent.

Passive components should be modelled to a circuit level simulation. This was done with an impedance analyser. A ferrite ring and grounding capacitors were modelled. Resistors were expected to be ideal. The ferrite ring was measured as a common-mode choke and an equivalent circuit was created with an ABB developed Circuit Model Generator software. The equivalent circuit is based on a separate differential and a common-mode inductance with some parasitic capacitance and resistance. A film capacitor was modelled as a series connected ideal capacitance, a resistance and an inductance. Those values were measured with impedance analyser.

A system level simulation was then created in Simetrix software. All equivalent circuits and components were placed and connected as it is done in a real life system. A solution type was AC-analysis which calculates simulation in a frequency domain. Both simulation and measurement results are presented as an insertion loss to make comparing easy. Also the simulation results of the differential and common mode noise is presented separately as it is measured. Comparison to the measurements were done in the MATLAB. To investigate EMI behaviour in lower frequencies the simulations were conducted with a frequency range 9 kHz to 30 MHz. The simetrix model of the simplified setup is presented in the appendix B.

Output power of the EMI generator was 0 dBm and an excitation of the simulation model was meant to be same. However, an impedance of an EMI noise circuit changes proportional to a frequency and then the supply voltage and current both changes even a power remain the same. This is not easily implemented to a simetrix AC-analysis where only an ideal voltage or current source can be used. However, the results can be compared based on the difference to a reference situation.

3.3 Measurements

Measurements supports the simulations and validate its results. The measurement system with the simplified model is meant to be easy to simulate and modify. The parasitic phenomenon are also minimized. Instead the measurements with a full drive system are the standard measurements for conducted emissions and its goal is to find out an actual EMC-level that a drive with an investigated solution would have.

3.3.1 Measurements with the simplified model

The simplified drive connector environment model was presented at the chapter 3.1. In this section a real life measurement system to research an inductive coupling, a shielding effectiveness and an effect of an EMI filter topology with that model is discussed. These measurement are presented in detail in the part 4.

The measurement system consist of an EMI noise generator/receiver, an EMI noise separator, coaxial cables and the designed measurement model. The EMI noise generator is connected to an EMI loop representing a motor cable with the coaxial cable. Induced noise is then measured with the EMI receiver as a spectrum analyser mode via the noise separator from the input phases. The drive's end of the phase conductors are terminated to ground with 50 ohm terminator. The measurement set-up is presented in the figure 6 at the chapter 3.1.

The used EMI noise generator/receiver was Rohde & Schwarz ESCI. The generator/receiver device injects a sinusoidal signal exactly at the measured frequency. The measured bandwidth was from 150 kHz to 30 MHz. The power of the EMI generator was set to maximum which is 0 dBm to keep a measured signal above a noise floor in all measurements. The EMI receiver was used in a spectrum analyser mode which means that it measures a voltage over 50 ohm resistor and calculates FFT (fast fourier transformation) from the measured signal and present its magnitude as a function of the frequency.[24]

A noise separator is connected between the simplified model and EMI receiver with coaxial cables. The separator separates a common-mode and a differential mode noise from the measured phase signal. The used EMI separator is designed by ABB. It provides a practical implementation to a mathematical formula of a common-mode and a differential-mode noise separation [25]. It is based on a common-mode choke. Each phase and a common-mode signal are measured separately and non-measured signals are terminated to ground with 50 ohm terminators.

Measurement results were saved as an ASCII format and post processing was done with MATLAB. The insertion losses were calculated and difference in the loss compared to reference situation were plotted. Comparison to simulations can also be done there.

3.3.2 Measurements with the drive system

Drive system measurements followed the standardized test for conducted emissions. A drive was running an induction motor without load and conducted emissions to grid were measured with LISN (Line Impedance Stabilization Network) and EMI receiver. Test standards are presented in the IEC 61800-3[14]. The test setup is presented in the figure 12.

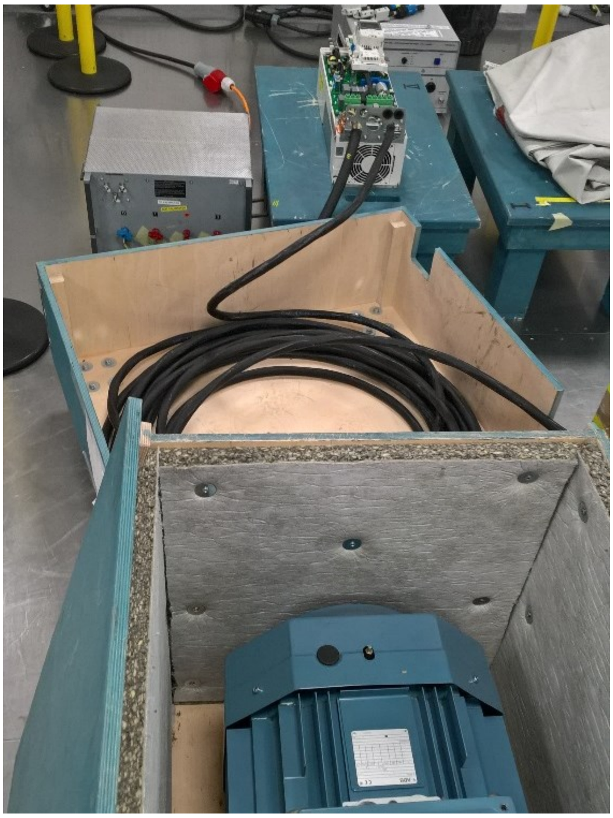

Figure 12. *The test setup of the drive conducted emissions*

The motor, the motor cable and the drive are all placed on insulated platforms over conductive test area. The LISN can be found on upper left corner of the picture and it's grounded to the test area. The EMI receiver is not seen in the picture but it is connected to the LISN with coaxial cable. The used EMI receiver was Rohde & Swartz ESRP. The Solutions tested with the drive system are discussed in the chapter 4.5.

3.4 Reliability and validity

Validity and reliability were main objectives for the simulations and measurements. In this study the validity is achieved when conducted research really investigate the discussed phenomenon. Reliability measures how accurate the research results were. The validity of the investigated set-ups and reliability of the simulations and the measurements are discussed.

3.4.1 Validity of the research set-ups

There was mainly two set-ups used in this research. The simplified model of a drive connection and a full drive system. The full drive system presents the standardized set-up for conducted EMI measurements. Its validity is therefore an irrelevant question. However, the simplifications done in the simplified model can be discussed.

In a simplified model only coupling between a drive's connections were investigated. This does not take account other noise sources in the drive which may also couple to grid connection. The second simplification is the shape of the opened grid and motor cables. In a real drive the cables may have a different shapes between a cable clamp and a connector. The investigated shape of the cables is the worst case with the largest possible loops.

The used noise power was significantly lower than in a real drive. The assumption was made that investigated phenomenon behave similarly also with a higher power. Also the effect of the EMI filter was investigated without a main choke of the drive. It was expected that only the first impedances at a grid side are significant. The measurements with a full drive system validate these assumptions.

3.4.2 Reliability of the simulations and the measurements

Reliability questions of the simulations and the measurements are different and are therefore discussed separately. The main question with simulations is that is the used software modelling all necessary phenomenon. The measurements do that for sure but are can be affected by noise from non-wanted sources.

The Q3D software is proved to be accurate to model parasitic couplings in a drive with many simulations before. The investigated set-up has also quite simple geometry so the reference set-ups should be simulated well. However, there was uncertainly how the Q3D can model a shielding and higher frequencies. The ability to model shielding was not tested before and because the Q3d models only a surface of the object there might be errors. The measurements shown that the shield that is far enough from the noise source is modelled correctly with only surface of the object but because the restrictions are not investigated the results should be used cautiously. The previous tests have shown that measurements and simulations differ with the frequencies above 5 MHz. Therefore the results are compared at 1 MHz frequency.

The measuring a coupled signals with solutions that effectively damp the coupling was a problem. The coupled signal have so low intensity in those measurements that part of the measurement noise was high. Because measurements and simulations followed each other in most cases the results are quite reliable. The simulations with the shield close to a noise source should not be used without measurements.

4. PROPOSED SOLUTIONS

Based on the presented theory a possible ways to reduce an EMI noise coupling in a drive connectors are identified. These solutions are categorised to three groups depending whether solution is based on a different connector positioning, an EMC shielding or an EMI filter topology. Each solution is simulated and promising simulated solutions are validated by the measurements with a simplified model of drive connections. The all results are compared with a reference situation which represents the existing connector area structure.

The combinations of effective solutions that were easy to implement to existing drive were also designed. This is researched with the simplified model and with the full drive system. A feasibility and a cost effect of the effective solutions are discussed. The more detail discussion about the results is in part 5.

4.1 Reference situation

The reference situation presents a current connector structure in an ordinary drive. There the motor and grid connections are side by side at the same level in and there is no EMC-shields placed. As presented in the section 4.2.2., there is probability of the significant inductive coupling. An EMI filter is also included the reference situation when investigating the effect of an EMI filter topology. Simulation and measurement results of this situations are the reference where the other solutions are compared. The simulation model of the simplified model of the reference situation without EMI filter is presented in the figure 13.

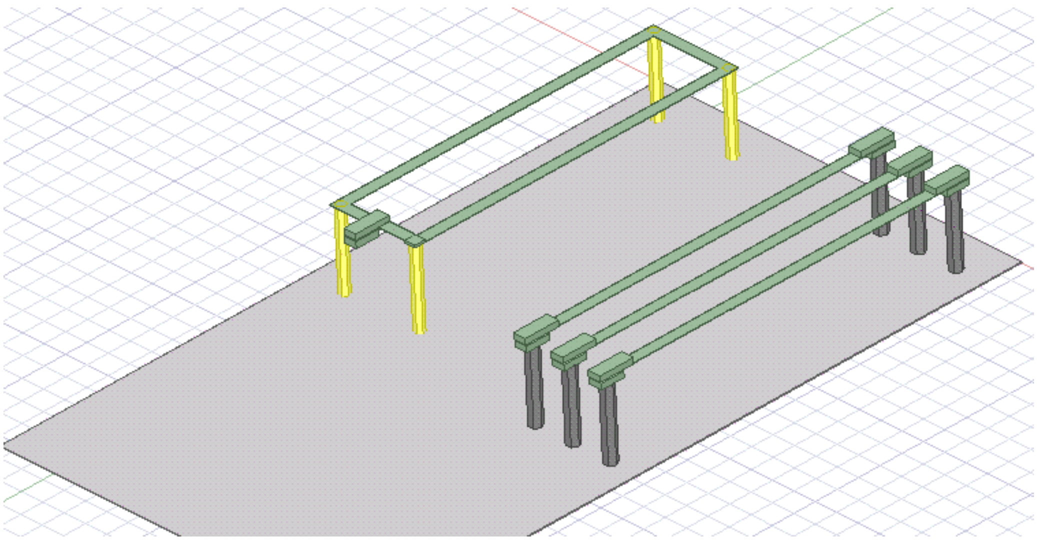

Figure 13. *The simulation model of the simplified model of the reference situation without an EMI filter.*

A real life measurement model was matched to a simulation model. The real life simplified model in the reference situation is presented in the figure 14.

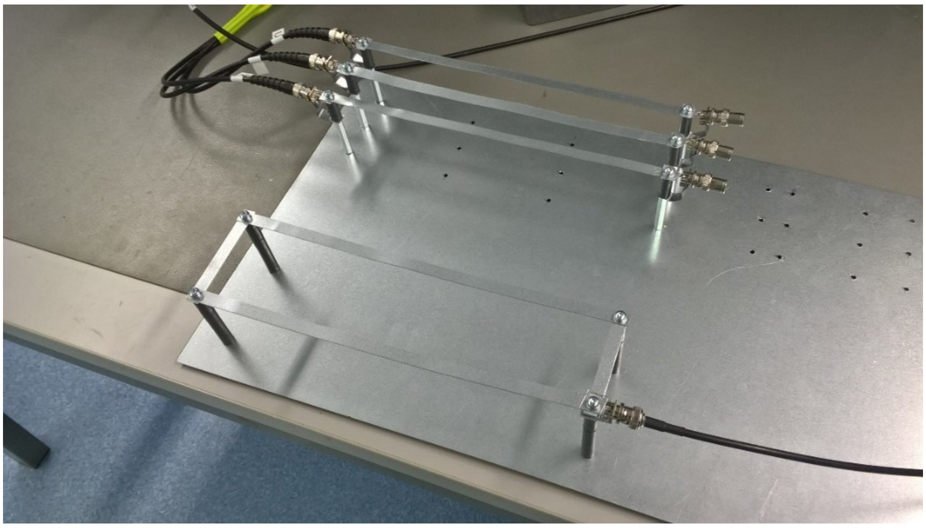

Figure 14. *The real life simplified model of the reference situation without an EMI filter*

The simulation and measurements of the reference situation without an EMI filter were conducted as presented in the part three and results of all phases were plotted to separate figures. The results are presented as an insertion loss calculated from measurement results in the figure 15.

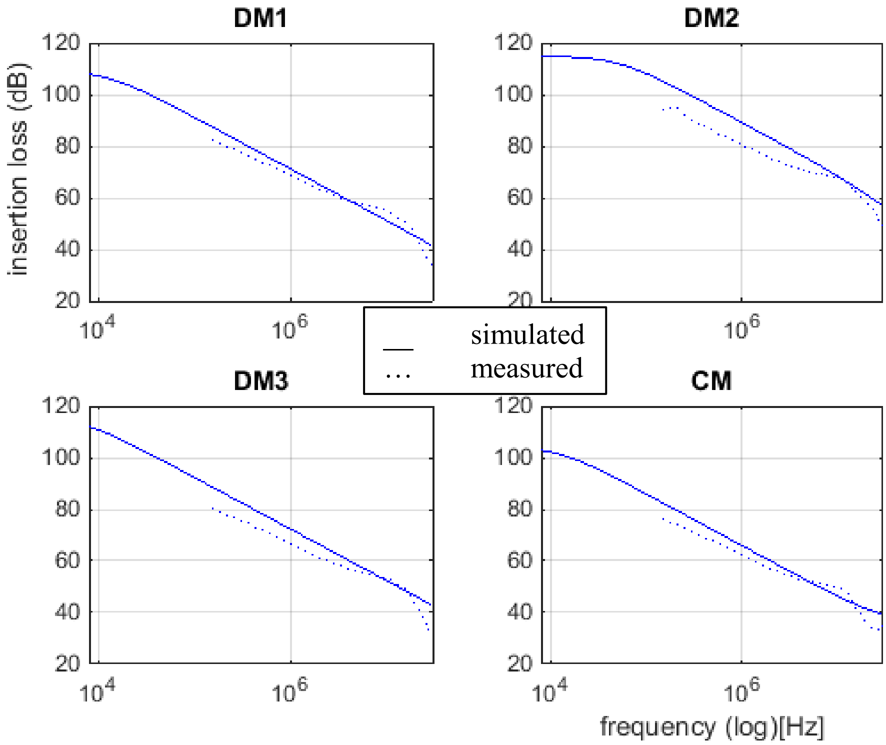

Figure 15. *Simulated and measured insertion loss of the reference situation without an EMI filter*

As can be seen from the figure 15 the common-mode noises have the smallest insertion loss. The insertion loss in the phases L1 and L3 is almost even and L2 is higher than two others. Absolute difference between noises in the different phases is simulated well even the shape of the trace is not the same. This is explained in the section 3.2.2. Simulations and measurements are later compared to these figures.

To make several changes in the model structure easier an EMI filter is installed only in measurements investigating the effect of the EMI filter. The ordinary filter consists of the grounded capacitors and a common-mode choke as presented in the section 2.1.5. The real life simplified model of the reference situation with the EMI filter is presented in the figure 16. The X-capacitor's capacitance was 1 µF and the Y-capacitor's capacitance was 860 nF.

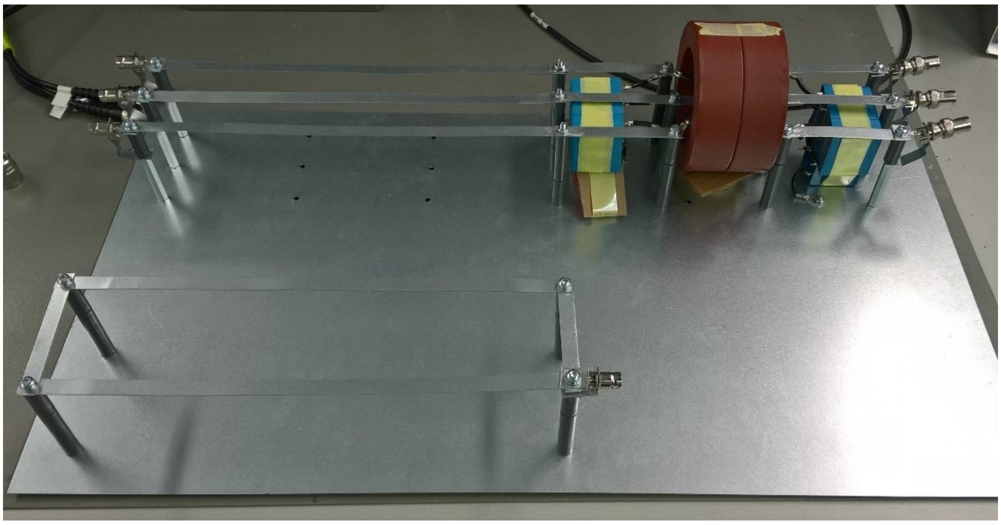

Figure 16. *The real life simplified model of the reference situation with an EMI filter.*

The reference situation with an EMI filter was simulated and measured. These results were later used to calculate an insertion loss compared to the reference situation with tested solutions similarly than in the measurements without the EMI filter.

4.2 Connector positioning

Positioning drive's connectors differently than in an ordinary structure would decrease an inductive coupling based on the theories presented in the part one. In a section 2.2.2 a three different solutions were identified. The first was to increase the distance between the coupled circuits and the second was to decrease the loop size of the coupled circuit. The last one was to place connectors so that induced magnetic field is parallel to a victim circuit.

In a drive there is design requirements and therefore connectors should be placed side by side in the same end of the drive. The investigated solutions are those that fulfil those requirements but apply a theory based solution. The sizes of the coupled circuits are based on the standards for an assembly space in a conduit box and an insulation gap between phase conductors so the effect of the loop size is not discussed.

4.2.1 Horizontal difference

Horizontal difference in drive's connectors means that connectors are placed to a different distance from the low end of the drive and not side by side. This should decrease a coupling because a distance between coupled loops increases. The real life measurement model with 10 cm horizontal difference is presented in the figure 17.

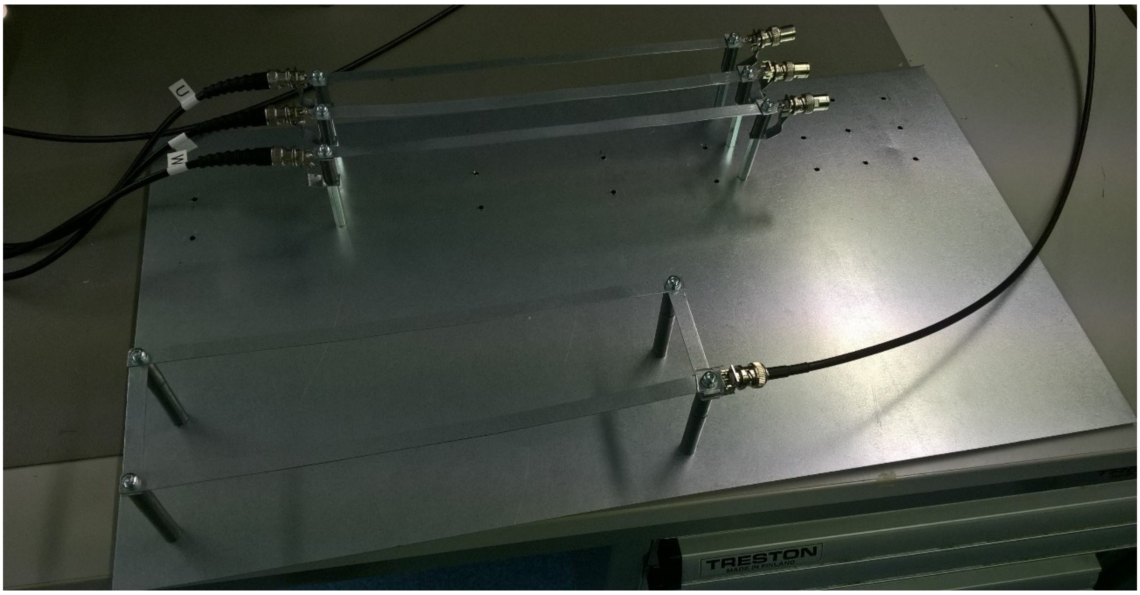

Figure 17. *The real life measurement model with 10cm horizontal difference*

The horizontal difference of 10 cm and 20 cm was simulated. Results shown that correlation between the horizontal difference and a coupled EMI noise is almost quadratic. The increase in an insertion loss with 10 cm difference was about 2 dB in all phases but 9 dB with the 20 cm difference. Both simulations were validated with real-life measurements. Simulated and measured insertion losses compared to the reference set-up with both distances is presented in the figure 18.

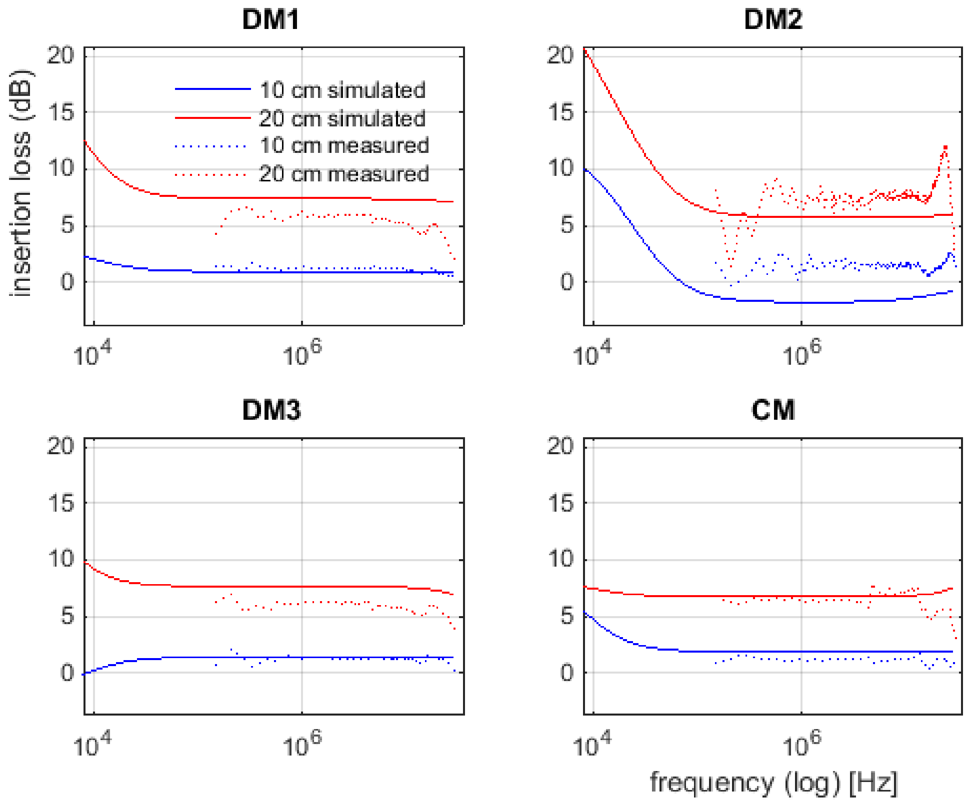

Figure 18. *Simulated and measured insertion losses compared to reference set-up of +10 cm and +20 cm horizontal difference*

As seen in the figure the measurements correlated well with the simulations. Notice that measurements and simulations have different frequency range as described in the part 3. Horizontal difference seems to affect similarly to both differential and common mode noise. The effect is similar through investigated frequency range except in phase two where horizontal difference is even more effective with low frequencies.

4.2.2 Vertical difference and distance to the ground plate

Assembling a grid connector to a different height from the ground plate than a motor cable connector makes more distance between coupled loops and should therefore decrease the coupling. It also causes the magnetic field of an EMI noise to meet phase conductors in more parallel angle which is a benefit. However, if the ground plate is in level and the distance between it and the conductor increases it may cause a larger common-mode loop and the common mode coupling.

To research this the coupled EMI noise was simulated with three different heights and the results were compared to the reference situation. Chosen heights were -5 cm, +5 cm and +10 cm compared to the reference. If the results between -5 cm and +5 cm situation are different the distance to ground plate is important. The simulation model of the +10 cm vertical difference is presented in the figure 19.

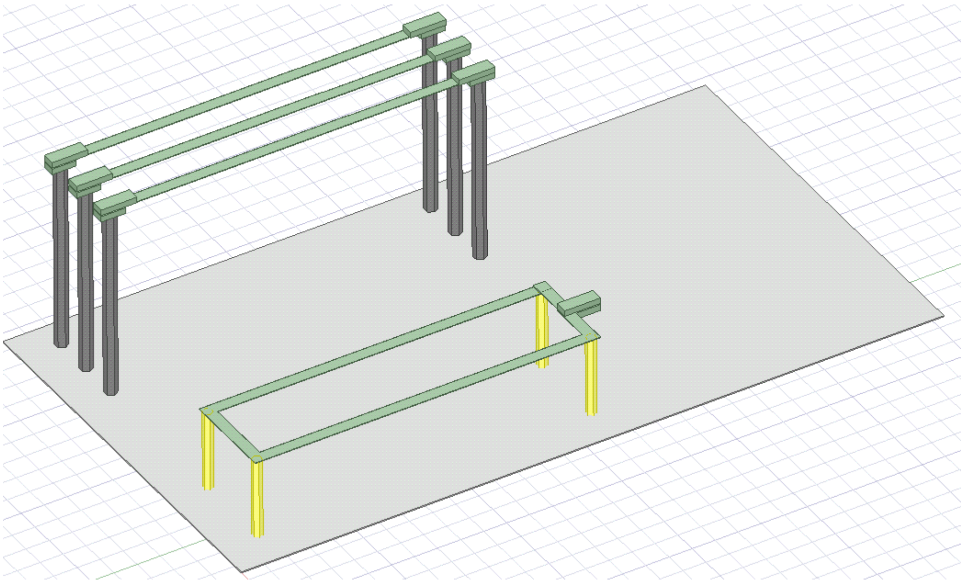

Figure 19. *The simulation model of the +10cm vertical difference situation*

Simulations predicted that a distance to ground plate is much more important than the distance to a noise source with the investigated distances because -5 cm position increased insertion loss by about 6 dB when there was no significant decrease with +5 cm position. +10 cm position reduces also coupling but not more than -5cm position. Simulated insertion losses compared to the reference set-up are presented in the figure 20.

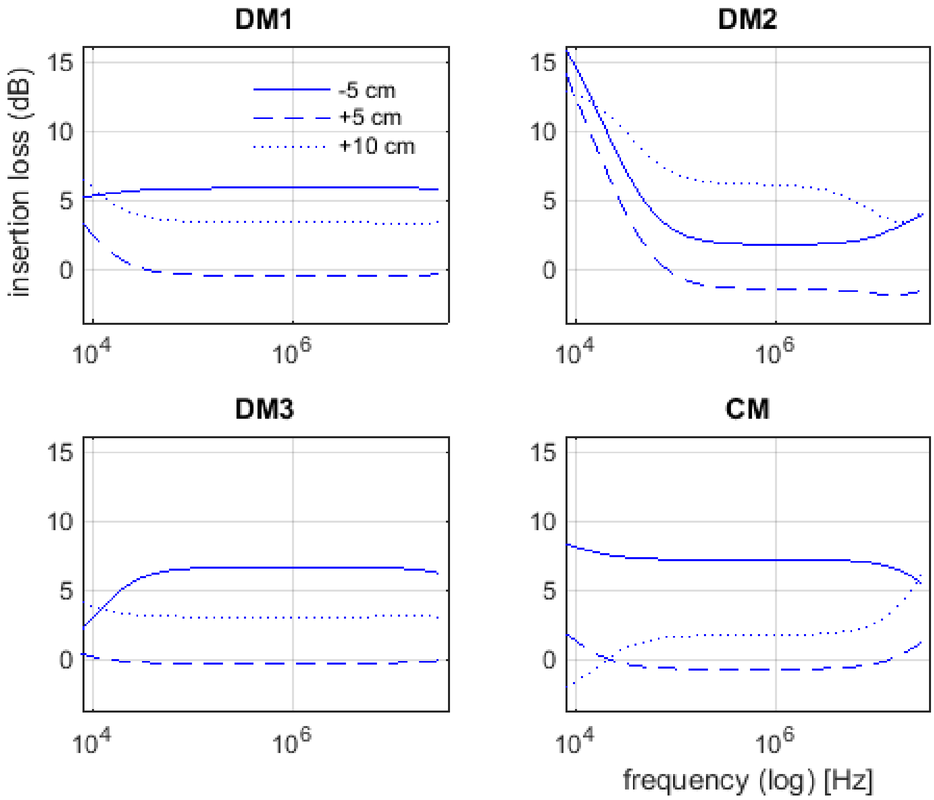

Figure 20. *Simulated insertion losses of the -5cm, +5cm and +10cm vertical difference compared to the reference set-up*

Difference between -5 cm and +5cm situations were also measured with a real-life measurements. The measurement results are presented in the figure 21.

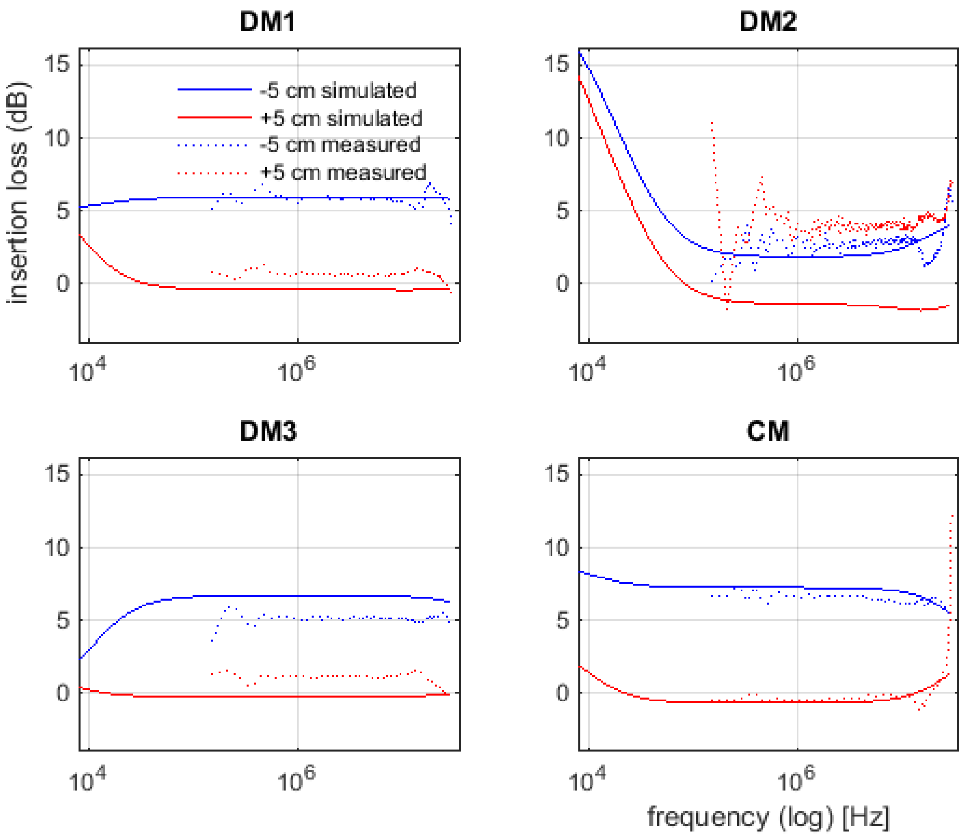

Figure 21. *Measured and simulated insertion losses of the -5 cm and +5 cm vertical difference compared to the reference set-up*

The results were similar to simulations and -5 cm situation caused more insertion loss than +5 cm which effect was almost zero. The measured result of the +5 cm difference in a phase two differ from the simulated result maybe due to a measurement error. The measured changes in effectiveness through an investigated frequency range were minor like in the horizontal difference research.

4.2.3 Angular difference

Angular difference between a magnetic field of an EMI noise and grid connectors is achieved by placing each conductor of the motor cable to the different height. When the magnetic field of the EMI noise is parallel to the phase conductors the coupling is decreased. Problem is that when the magnetic field is parallel to the differential loop of the phase conductors it is perpendicular to the common-mode loop. This may lead to a higher coupled common-mode noise.

The optimum angle between grid and motor conductors is identified with simulations so that coupling magnetic field and the grid conductors have 180 degrees angle between. Simulations shown that it is achieved when the motor cable conductors form a loop that have the 35 degrees angle to a ground plate. It was also seen that it is better to place a conductor that is closest to a grid cable close to a ground plate. Simulated EMI noise magnetic field is presented in the figure. This simulation was done with ANSYS Maxwell software. The simulated EMI noise magnetic field is presented in the figure 22.

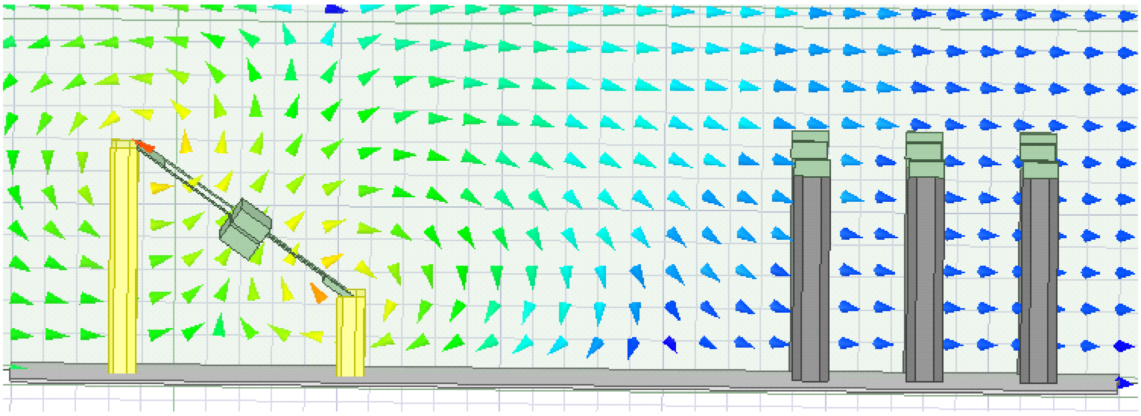

Figure 22. *The simulated EMI-noise magnetic field.*

The Q3D simulation was done using same model than presented in the figure. This simulation of the coupled EMI noise with angular difference shows a significant reduction in a coupled differential mode noise which decreased by 11 dBuV. A common-mode noise was increased by 2 dBuV which was expected based on theory. The results are presented in the figure.

In real-life measurements the 35 degrees angle to motor cable conductors was implemented by placing one conductor to a height of 25 mm from a ground plate and another to a 70 mm height. The real-life measurement model is presented in the figure 23.

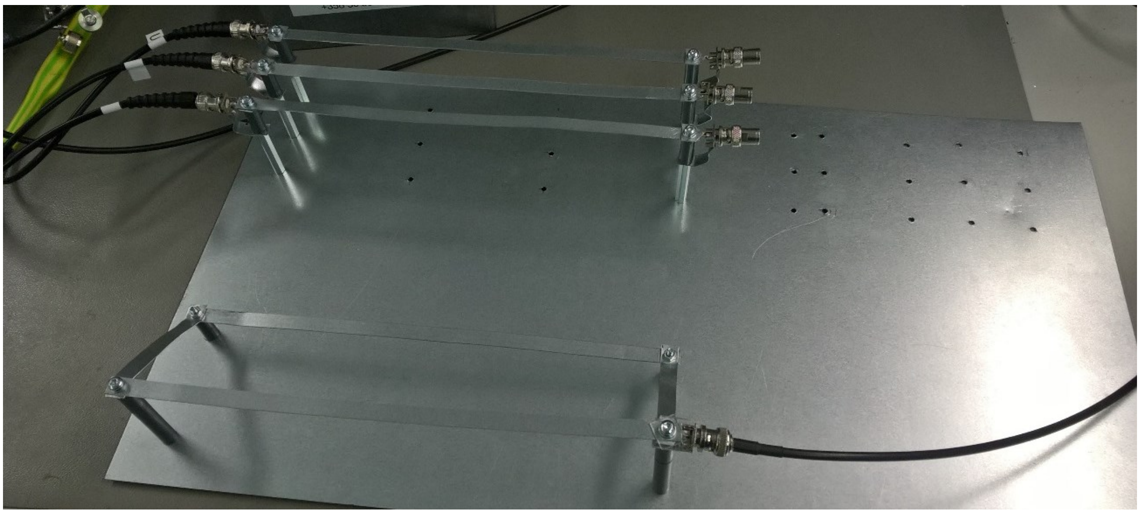

Figure 23. *The measurement model of the angular difference situation*

The phase conductors were on reference position. The simulated and measured results of the 35 degrees angular difference are presented in the figure 24.

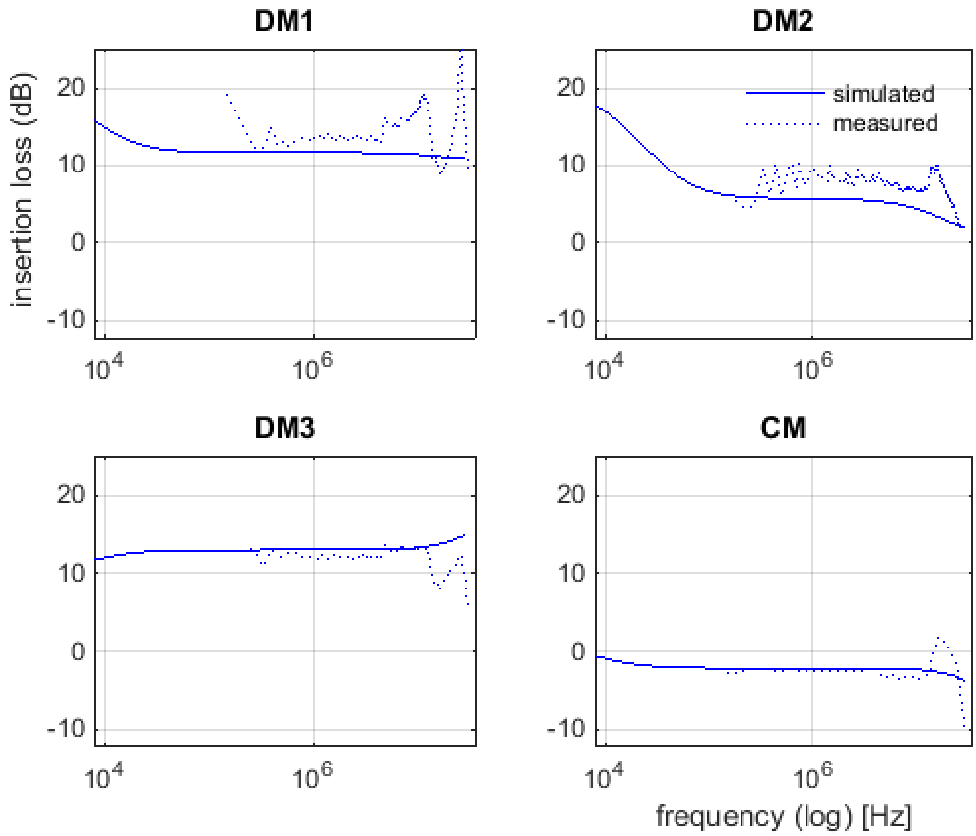

Figure 24. *Simulated and measured insertion losses compared to the reference set-up with 35° angular difference*

The real-life measurements correlated well with the simulations and angular difference seems to be effective solution for a differential mode noise but not for a common mode noise. It is effective through an investigated frequency range. Problem with this solution is that it is difficult to implement to a drive.

4.2.4 Combined solutions

In this combined solutions section the combinations of the previous solutions are tested to define how those function together. Horizontal and vertical differences can be implemented in a same device and it is important to know if implementing one solution has an effect to another.

The tested combination was to join vertical and horizontal differences. The best vertical solution was -5 cm which increased an insertion loss by 5 dB compared to reference level and maximum horizontal difference +20 cm did about 8 dB. The measurement model of the combined the vertical and the horizontal difference solutions is presented in the figure 25.

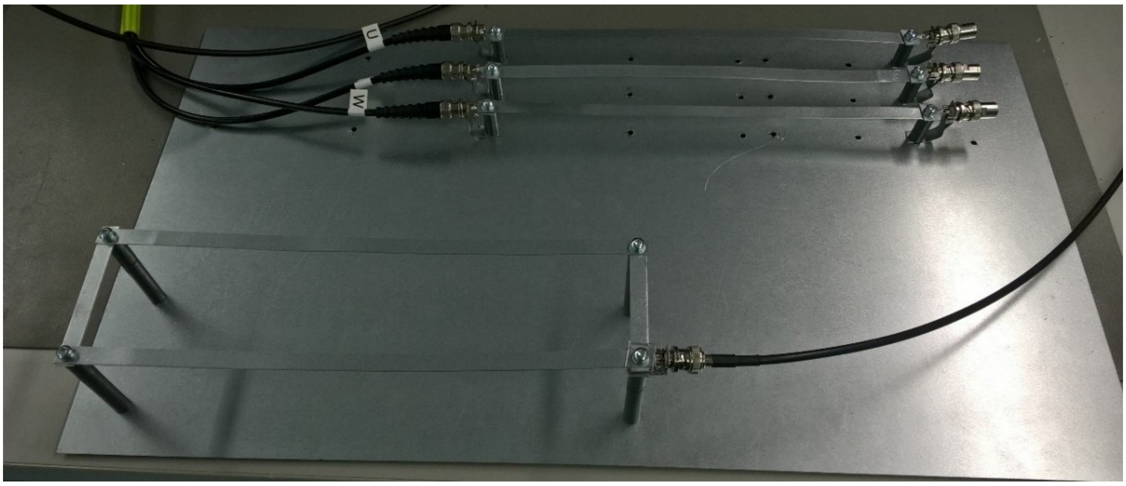

Figure 25. *The measurement model of the combined the best vertical and horizontal difference solutions*

The simulations predicted that in this case combining the solutions is effective with about 12 dB increase in an insertion loss even though there was about 1 to 2 dB difference between the result and the sum of the combined solutions. However, this is just 10 to 15 percent difference. Measurements supported these results. Simulated and measured results are presented in the figure 26.

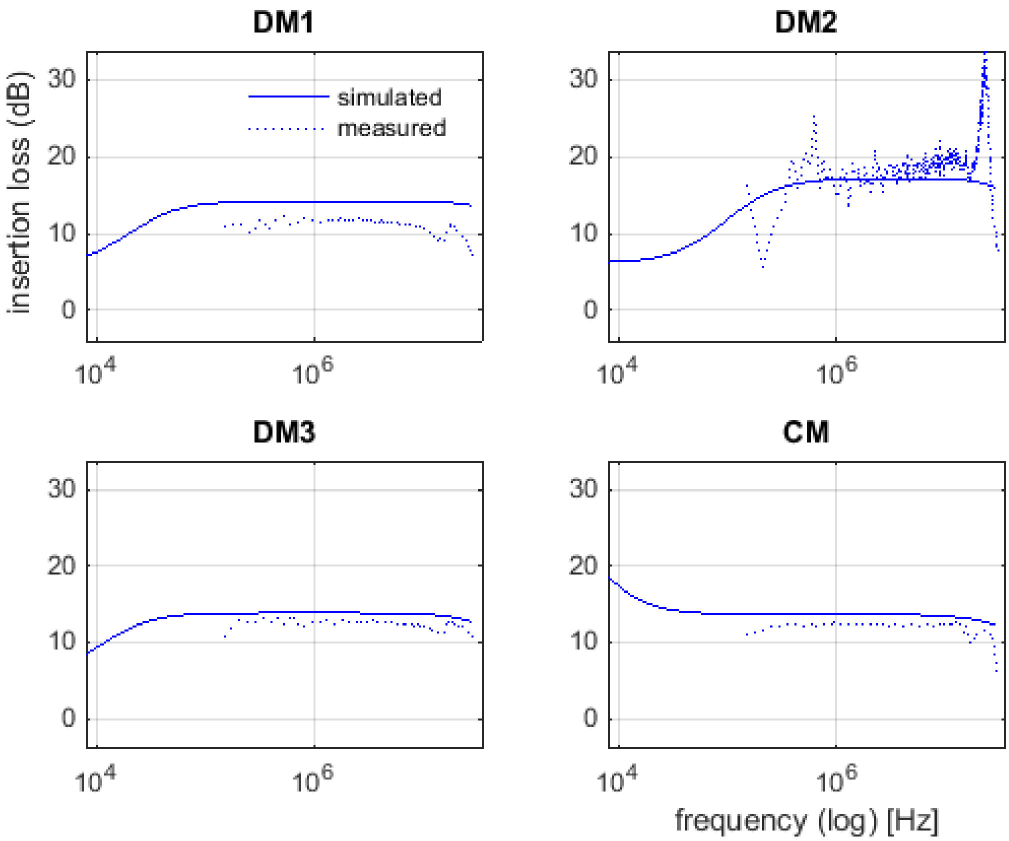

Figure 26. *The measured and simulated insertion loss of the combined -5 cm vertical and +20 cm horizontal difference*

There is only a relatively small difference in the results of the simulations and measurements. Combining solutions together seems to be effective and increase in insertion loss is almost a sum of the combined solutions. However, the results shows that combining is less effective with lower frequencies because the coupling is completely damped there and the results cannot be any better.

4.3 EMC Shielding

According the theory presented in the section 2.3.1 an EMC shielding could effectively decrease the magnetic coupling between grid and motor connections based on an absorption loss, a shorted turn effect and a magnetic field diversion with magnetic materials. In this chapter these techniques are applied to shields and those shields are simulated and tested. The results are compared to a reference situation without an EMI filter.

4.3.1 Plate shields

In conductive shields an absorption loss is the most important mechanism for shielding. It occurs in all metallic shields when an eddy-currents create resistive losses but its effect can be amplified with a material and geometry decisions. Based on the theory of the absorption loss discussed in the section 2.3.1, aluminium and steel shields were chosen to be tested. The both investigated plates were 1 mm thick. The aluminium have better conductivity and should therefore have higher absorption loss. However, the steel is also a reasonable good magnetic material at investigated frequencies. The use of special magnetic materials should be better only at low frequencies as presented in the section 2.3.1.

In this case the most convenient shield would be a box over either motor cables, grid cables or both. The cables go in and out from the different ends of the box. The length of the shield was set to cover grid connections all over and it was 380 mm. These three options were investigated. Simulation model of the shield in a grid connection is presented in the figure 27.

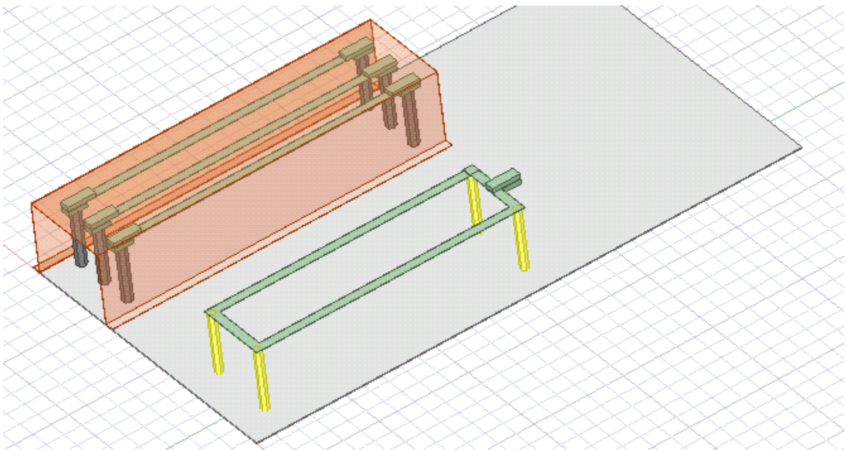

Figure 27. Simulation model of the shield in a grid connection

There was uncertainly how Q3D can model shielding with it limitations as discussed in section 3.2.1. This was tested at first to decide whether simulation results are used in this part of the study or not. Aluminium and steel shields on a grid connection were simulated and measured and the results are presented in the figure 28.

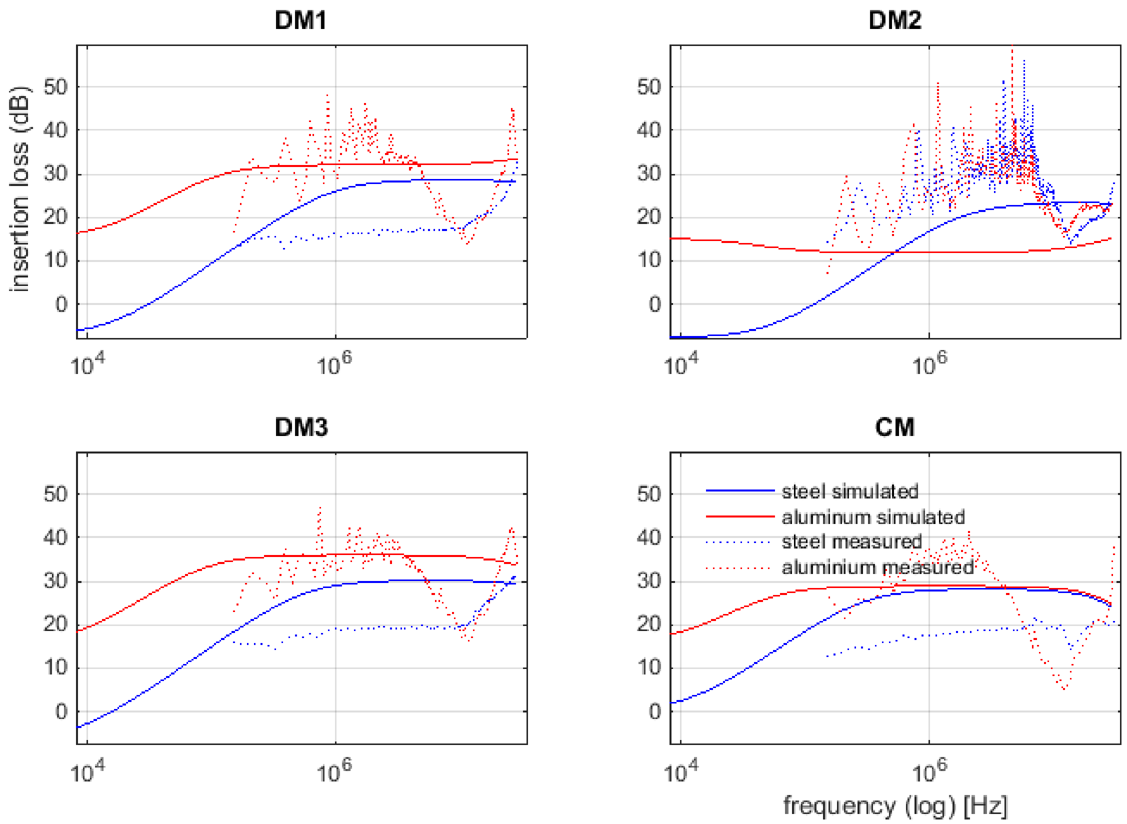

Figure 28. *Simulated and measured insertion loss compared to the reference set-up with the aluminium and steel shields on the grid connection*

As seen in the figure 28, the effect of the shield on a grid connection is simulated incorrectly even there is some similarity in the results. The Q3D seems to model shielding in some extent but probably the inability to model eddy-currents and currents inside objects causes too optimistic results. This was an expected result and therefore the Q3D simulations are not used with shielded set-ups.

The measured results can be used and there it can be seen that both materials are very effective as a shield. The shielding effectiveness is good through an investigated frequency range. The aluminium seems to be better at the lower frequencies but difference is closed at the higher ones.

The shields of the both materials were measured also on the motor connections and the results are presented in the figure 29. The shield on the motor connection is closer to the noise source and can therefore be more effective.

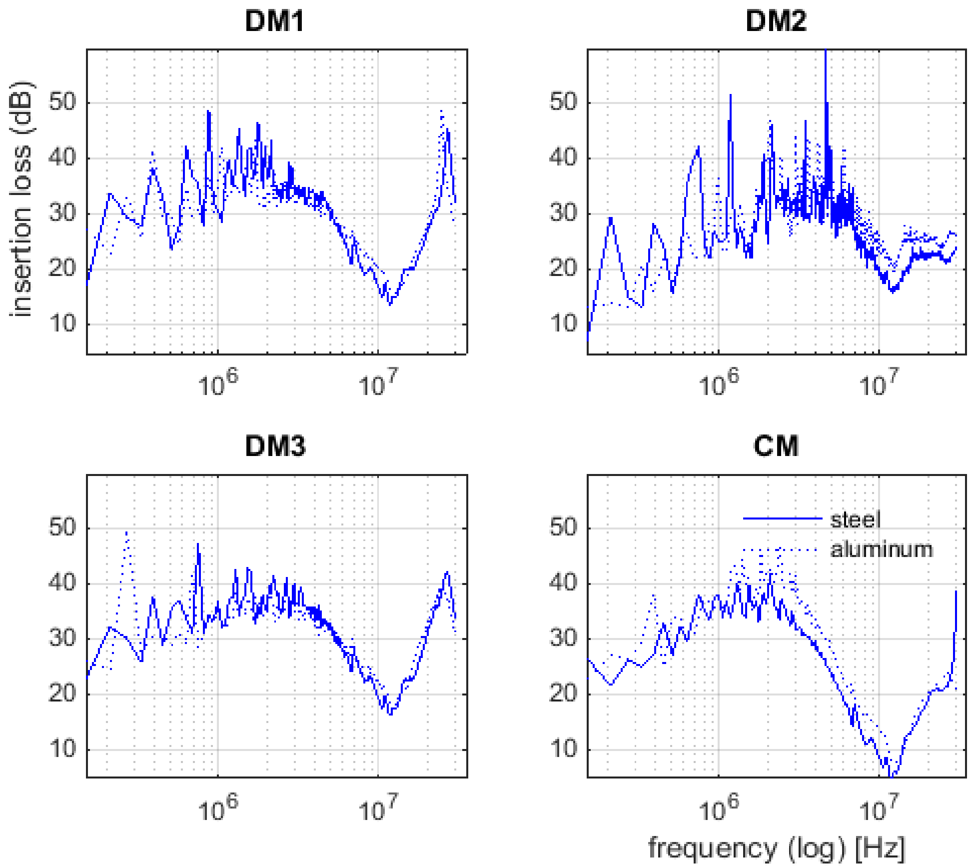

Figure 29. *Measured insertion loss with aluminium and steel shields on a motor connection*

As can be seen from the figure 29, there is no significant difference between aluminium and steel effectiveness when a shield is on a motor connection. The both shields provided a significant reduction in the coupling. The measured insertion loss is a bit higher than with the shield on a grid connection but there is more variation over an investigated frequency range.

The shield of both materials were also tested over both connections. This would be a too complicated solution for drive but results can be used to estimate how much the coupling can be reduced. The measurement results are presented in the figure 30.

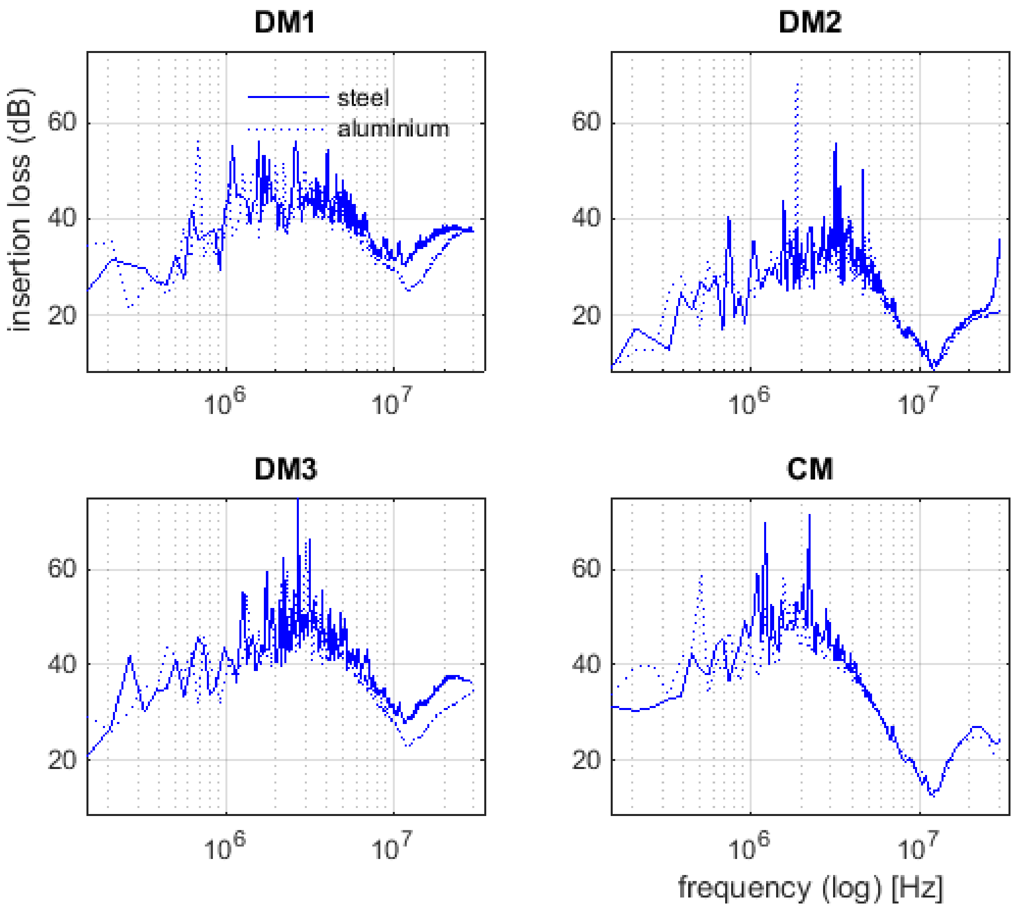

Figure 30. *Measured insertion loss with aluminum and steel shields on both connections*

Placing the shield over both connections did not provided much more insertion loss compared to one shield on motor connection. The variation over the measured frequency range is also similar than with the shield on motor connection. It seems that the one shield can reduce the most of the coupling. There was no significant difference between used materials.

The geometry of a shield could effect on shielding effectiveness. In a theory the significant parameters are the length of the shield and the biggest dimension of an aperture for the cables in the end of the shield. To investigate that the two different shields were simulated and measured. A square shape box with and without end plates where only small apertures for cables are. In this study the investigated frequencies are under 30 MHz and in a theory the apertures that are under 1/10 of a wavelength should not have an effect. This distance is 99,3 cm with 30 MHz frequency. The shield with end plates is presented in the figure 31.

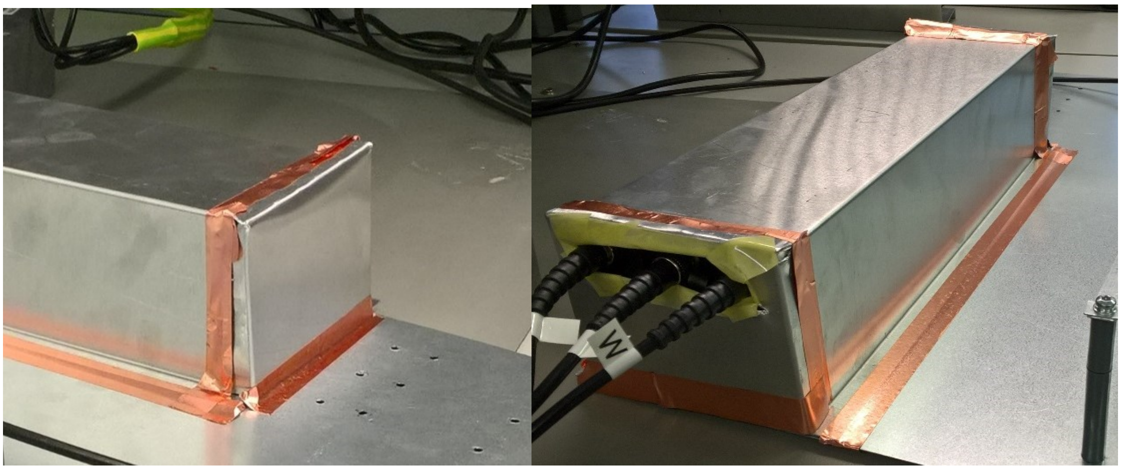

Figure 31. *The shield with end plates on a grid connection*

The simulations and measurements support the theory. The effect of the end plates is marginable as seen at the measurement results presented in the figure 32. The traces are almost one on the other.

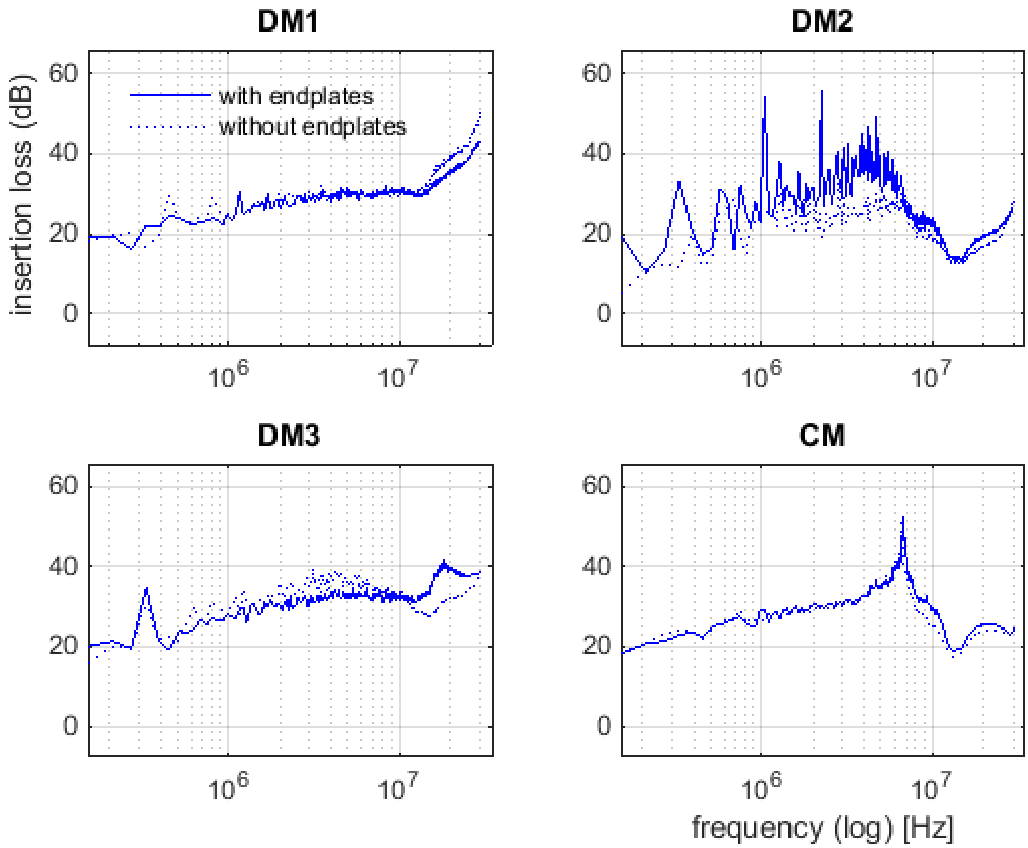

Figure 32. *Measured insertion losses compared to the reference set-up with the shields with and without end plates on a grid connection*

In a drive a heat is always a problem. Therefore a tight closures should be avoided which may be possible without reduction in a shielding effectiveness at an investigated frequencies as shown in the previous measurements about the end plate's effect. This makes maybe also possible to use a metallic net instead of a plate. This would lead to better ventilation under shield. However, shielding effectiveness can decrease because of an amount of a material where an eddy-currents can be created is significantly reduced. Shielding effect of the 10 mm x 10 mm eyes steel net shield made from 1 mm wire was simulated and measured. The simulation model of the net shield is presented in the figure 33.

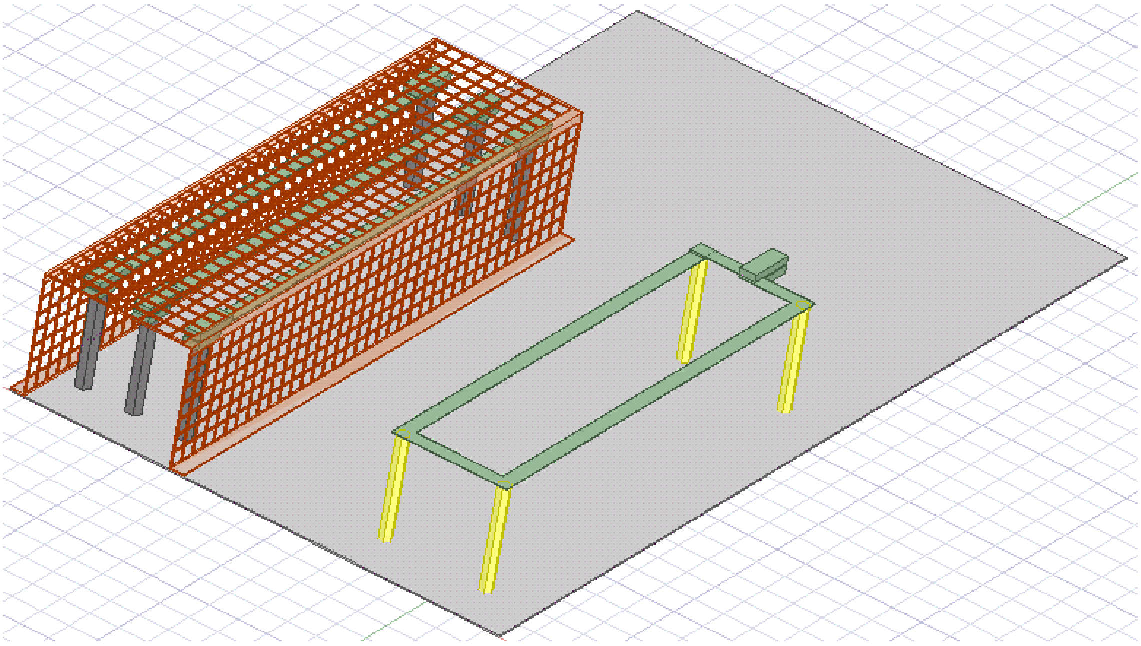

Figure 33. *The simulation model of the net shield on a grid connection*

The results are compared to a steel plate shield discussed before in this section. The geometry and measures between shields was identic. Measured results are presented in the figure 34.

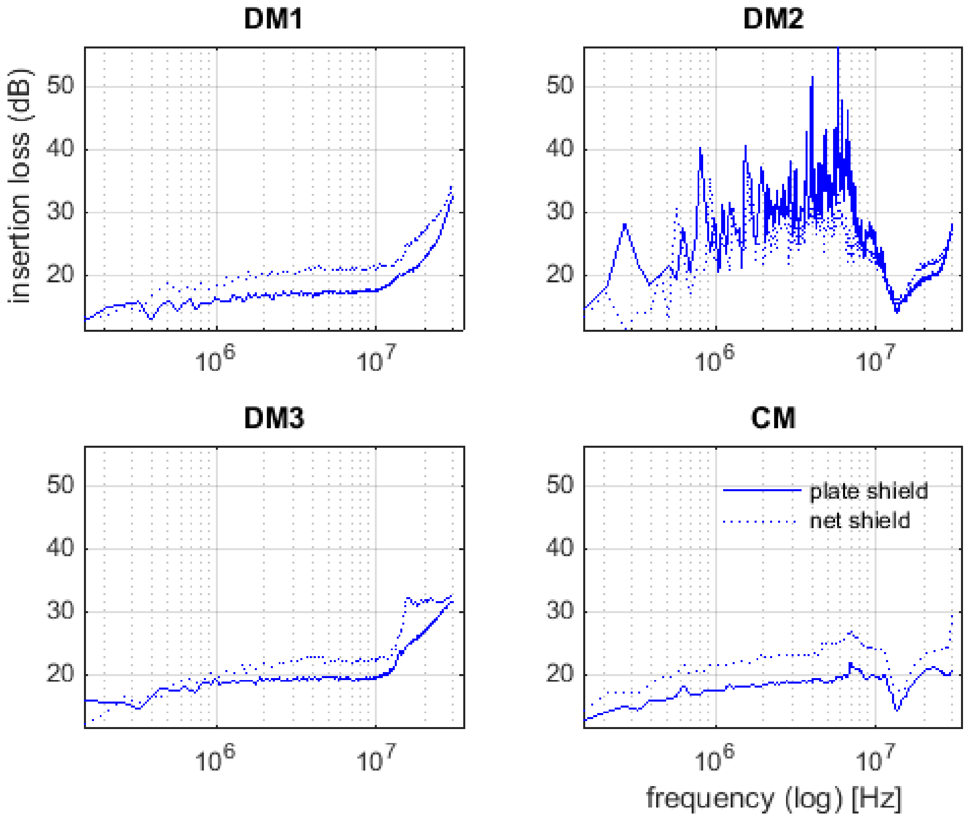

Figure 34. *Measured insertion losses of the plate shield and the net shield on a grid connection compared to the reference set-up*

As shown at the figure 34, the net shield is almost as effective as plate shield. There is no significant difference in an insertion loss through an investigated frequency range. This makes a net shield possible solution for a heat sensitive drives.

4.3.2 Shorted turn effect shield

This shorted turn shield would be good for heat problems but it is also easier to implement in drives. It is a shield that is based on a conductive wire loop that creates a cancelling magnetic field to a magnetic interference which goes through loop. The shorted turn effect is discussed in the section 2.3.1.

An effect of this kind of shield was simulated with a wire loop which size was 380 mm x 180mm. Loop was tested on both motor and grid connections and placed to the same level with conductors. The shorted turn shield should be more effective on the motor connection based on theory. This because then the whole interfering magnetic field goes through loop creating more cancelling field. Simulation model of a shorted turn shield on the motor connection is presented in the figure 35.

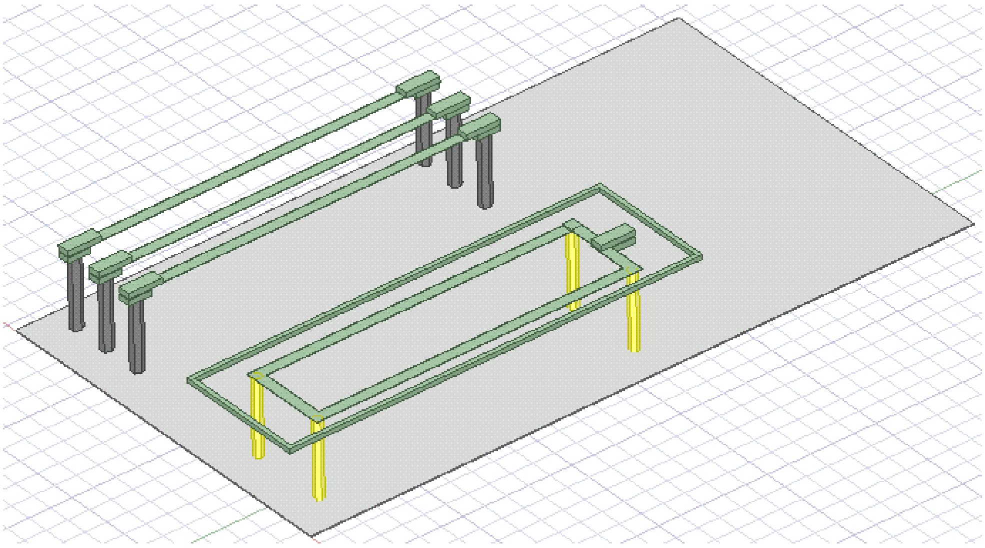

Figure 35. *Simulation model of the shorted turn shield on the motor connection*

Simulations shown that a shorted turn shield is more effective on a motor connection as was predicted. Damping is about 2 dBuV when the shield on a grid connection and about 6 dBuV on a motor connection. The shorted turn shield was simulated on both connections and measured on a motor connection. The results are presented in the figure 36.

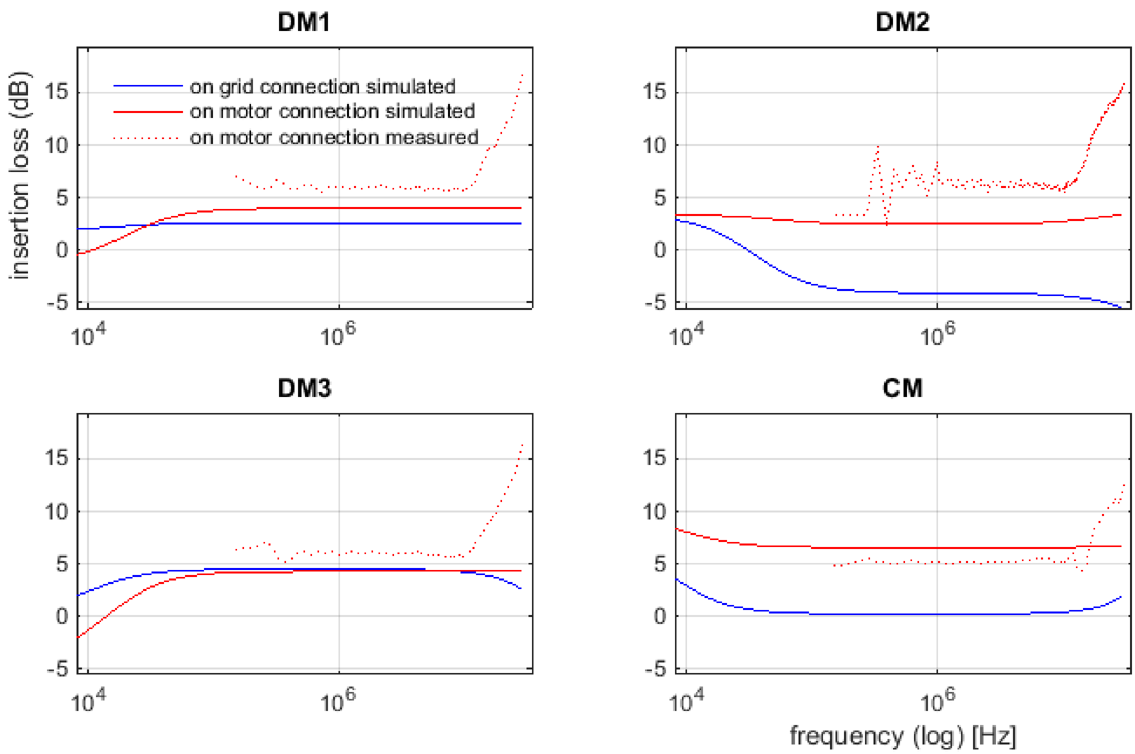

Figure 36. *Simulated and measured insertion losses compared to the reference set-up with the shorted turn shield either on the grid or the motor connections*

The measurements matched to simulations and the increase in an insertion loss was about 6 dB in all phases. The effect to insertion loss is constant through investigated frequency range. However, the shorted turn shield is not very effective compared to 20 dB insertion loss with other shields.

4.4 EMI filter topology

An EMI filter is a part of the circuit where a possible interference from the motor connection can be induced. The filter may amplify or damp an inductive coupling to circuit as presented at the section 2.2.3. The possible solutions to research at this chapter were identified based on the theory presented in the part one. Those are placing a common-mode filter to the grid side of the capacitors, removing the grid side capacitors, minimizing the differential loop by capacitor placement and shielding of the EMI filter. All solutions aim to decrease the differential mode coupling because a common-mode coupling is not be problem due to effective common-mode filter.

4.4.1 Increasing differential inductance of the grid connection of a drive

Increasing the amount of the differential inductance adds more differential impedance to a grid connection of a drive and should therefore damp induced differential interference as presented in the section 2.2.3. Differential inductance can be added to the grid connection by removing the grid side capacitors of an EMI filter, by placing an additional common mode choke to the grid connection or by increasing turns of the common mode choke. Increasing the turns may saturate a core material of the choke and cause also more heat inside the drive and is therefore avoided in many cases. Differential inductance in the common-mode filter is created due to the leakage inductance.

Removing the x-capacitors at the grid side of the common-mode filter removes the differential loop without inductance at the grid connection. This directs the coupled differential noise through a common-mode filter which have differential leakage inductance. The drawback of this solution is that it reduces the order of the differential mode filter. The measurement model without grid side capacitors is presented at the figure 37.

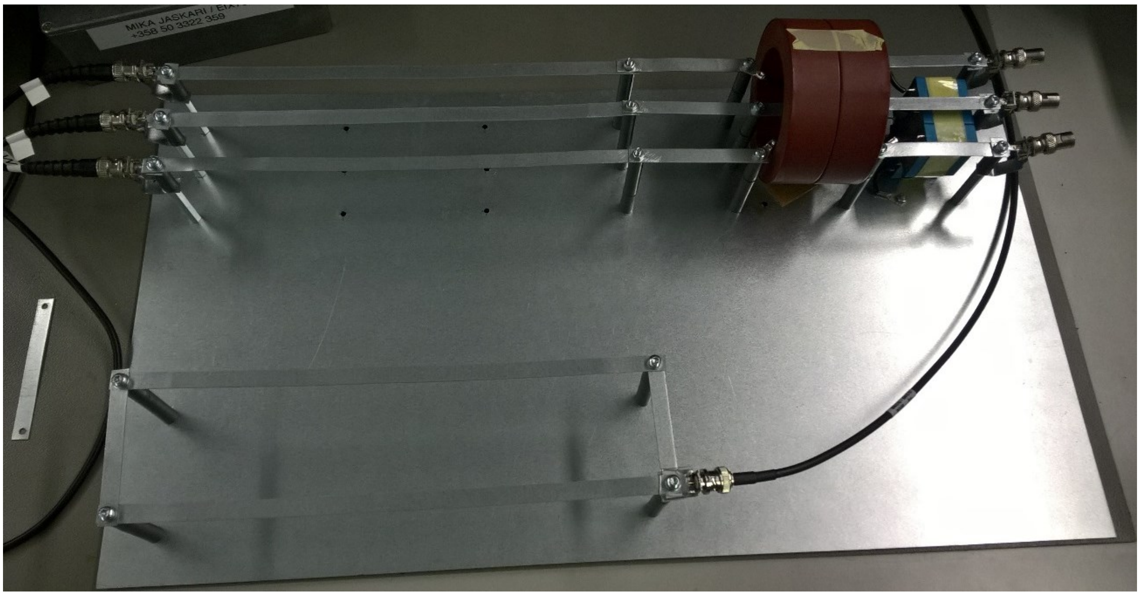

Figure 37. *Measurement model without grid side capacitors*

Additional common-mode filter at the grid side of the EMI filter cause a similar differential leakage inductance to the drive connection than the one filter with removed grid side capacitors. The benefit of this topology is that the order of the EMI filter remains the same but the drawback is the additional components needed. The simulation model of the topology is presented in the figure 38.

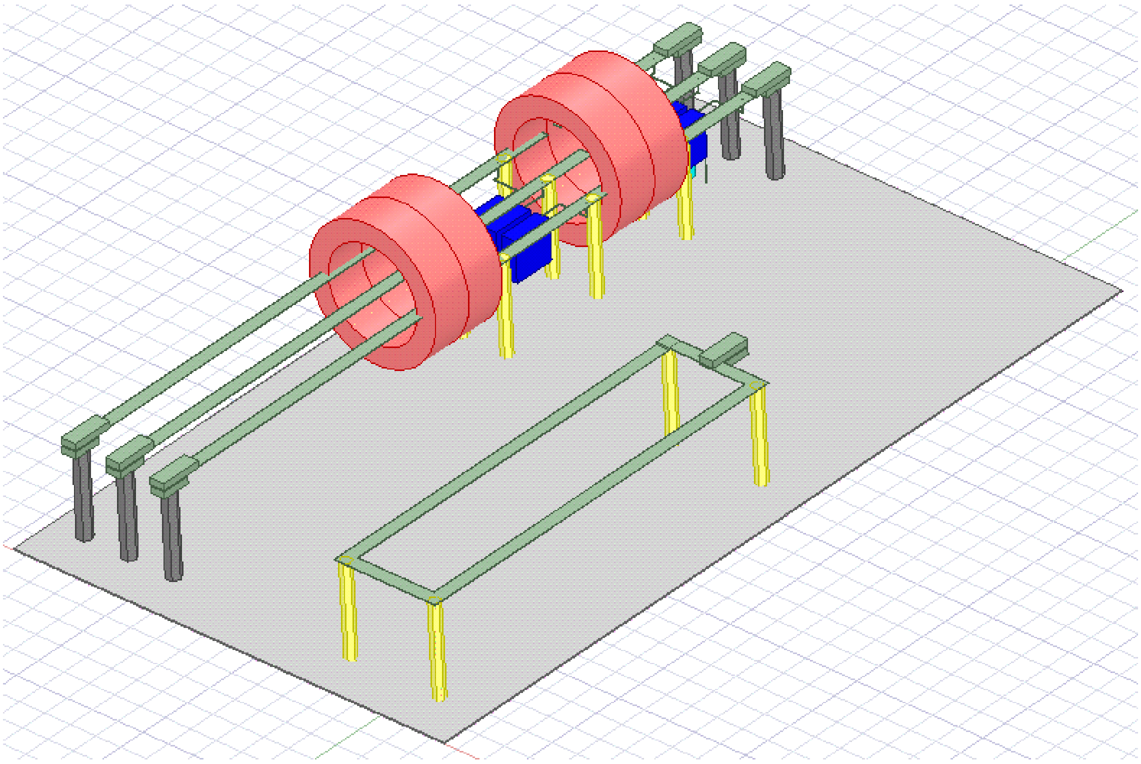

Figure 38. *Simulation model with 2 additional ferrites on the grid connection*

The removed capacitors and the additional common choke solutions should behave similarly with the coupled EMI noise due to the same amount of the differential leakage inductance before the first capacitors of the EMI filter that closes the differential loop. Both solutions were simulated with a simplified model of the drive connection environment and the results are presented in the figure 39.

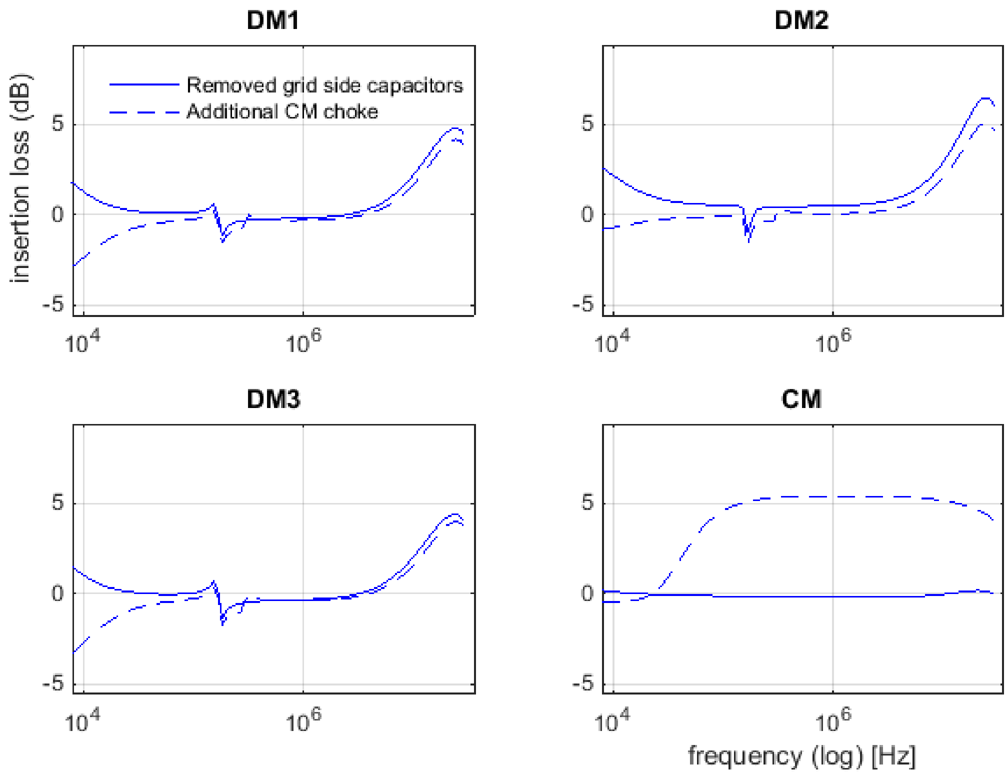

Figure 39. *Simulated insertion losses with removed grid side capacitors and with an additional CM choke compared to reference set-up*

As seen in the results presented in the figure 39, the removing the grid side capacitors and adding an additional common mode filter have similar effects to the differential coupling. However, it is also seen that a differential inductance of the tested common mode filter is not enough to have an effect to the coupling and an induced interference can flow through the capacitors at the device side of the EMI filter.

The investigated common-mode filter core was made from high permeable nanocrystal material and its leakage inductance is therefore low. The better results may be achieved with ferrite cores which creates more leakage inductance due to the lower permeability. The measured differential inductance was 0,1 µH. Simulations shown that 10 µH differential inductance would be enough to have significant reduction in insertion loss as seen in the figure 40.

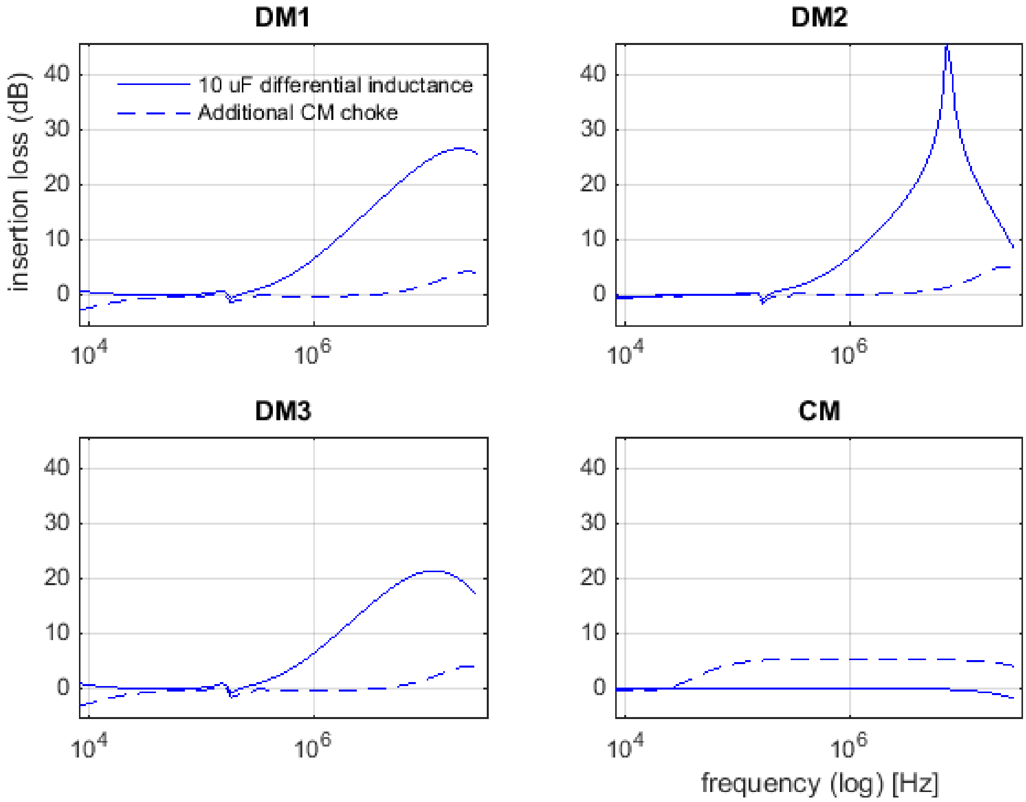

Figure 40. *Simulated insertion losses with 10 µF differential inductance added to CM filter compared to the reference set-up*

The differential inductance about this size can be achieved with ferrite cores or with more turns in the EMI filter. If a drive contains an AC common mode main choke this inductance is provided for sure.

4.4.2 Capacitors placement at the grid side

The placement of the grid side capacitors have an effect to the differential coupling as presented at the section 2.2.3. The loop that is formed between the capacitors and the grid connection is smaller when the capacitors are close to it. This should lead to reduced coupling. The capacitors placed grid's end of the measurement model were simulated and measured to investigate this. The measurement model of the capacitors placed to the grid's end of the model is presented in the figure 41.

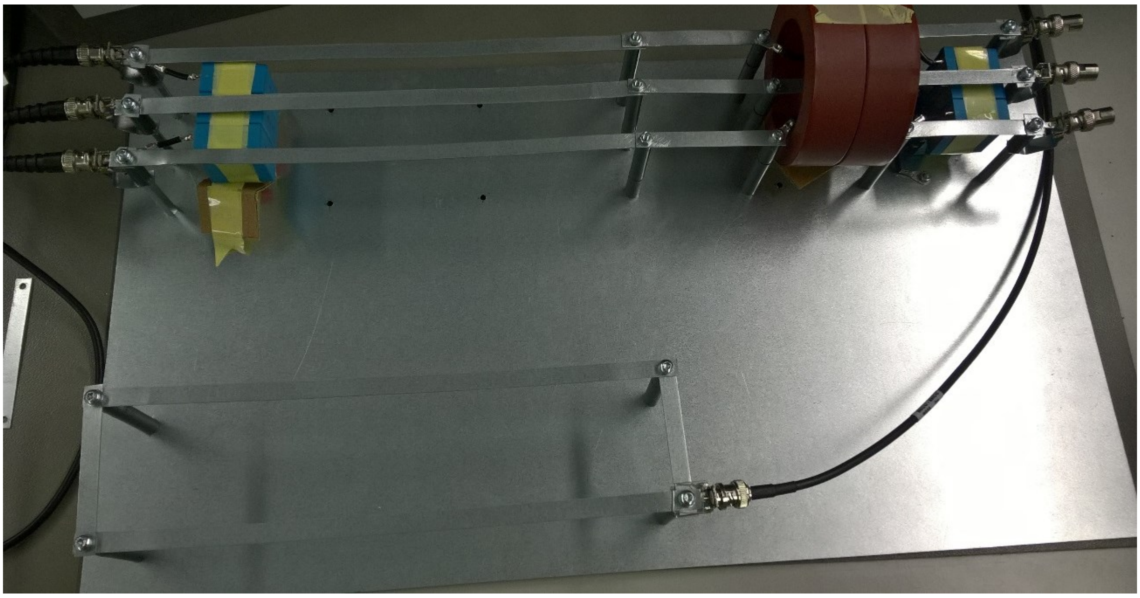

Figure 41. Measurement model with capacitors placed close to the grid connection

The simulated and measured results are presented in the figure 42. It is seen that by changing the capacitor placement, the insertion loss is increased about 10 dB in differential noise measurements which is a good result. The common-mode measurement is constant.

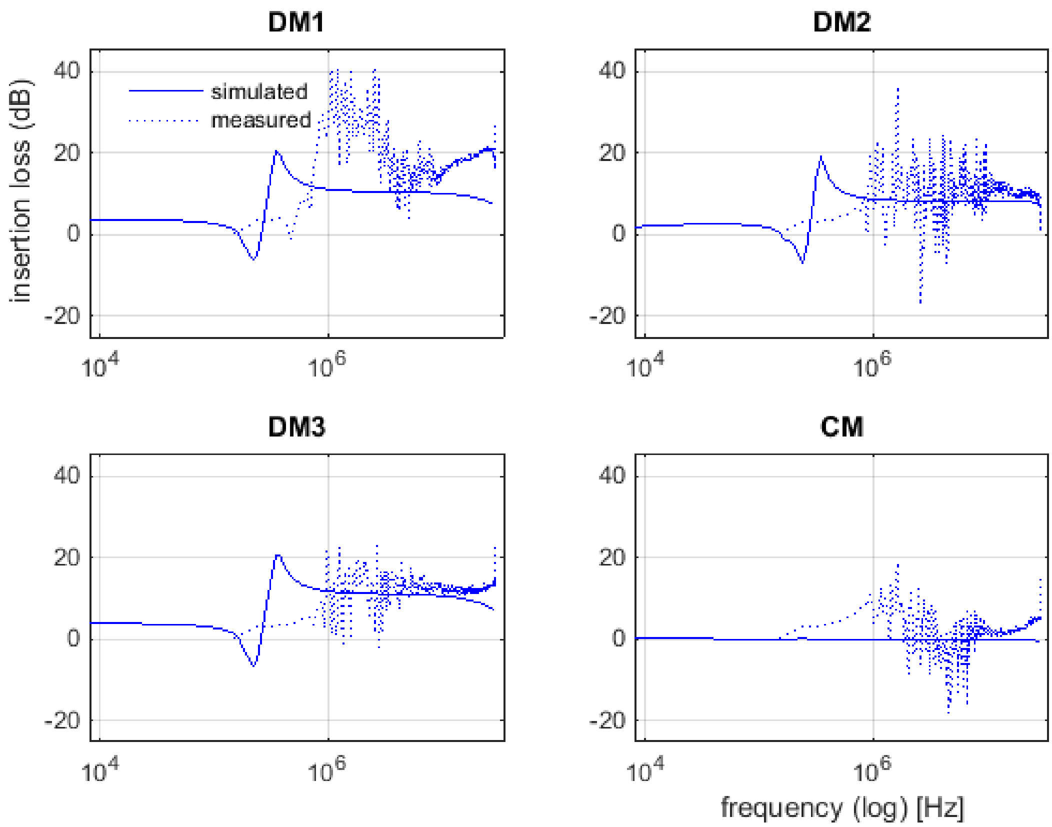

Figure 42. Simulated and measured insertion losses with grid side capacitors close to the grid connection

There is a resonance peak seen in a simulated results. This is maybe caused by interaction between the filter capacitors and differential inductance of the phase conductors. It should be minimized with the correct component sizing in the actual drive. Measured results have a lot of variation due to relative low measured signal strength.

4.4.3 Shielding the EMI filter

EMI filter is connected to grid connection of a drive and therefore a magnetic interference coupled to it is conducted to a grid connection. Especially capacitors of the filter are sensitive to coupling. The shielding of the EMI filter may therefore be more effective than shielding a connectors. To investigate this a shielded EMI filter in the simplified model was measured. The simulation were not used due to an inaccuracy noticed in the section 4.3.1. However, the simulation model of the shielded EMI filter is more informative than a picture and is therefore presented in the figure 43.

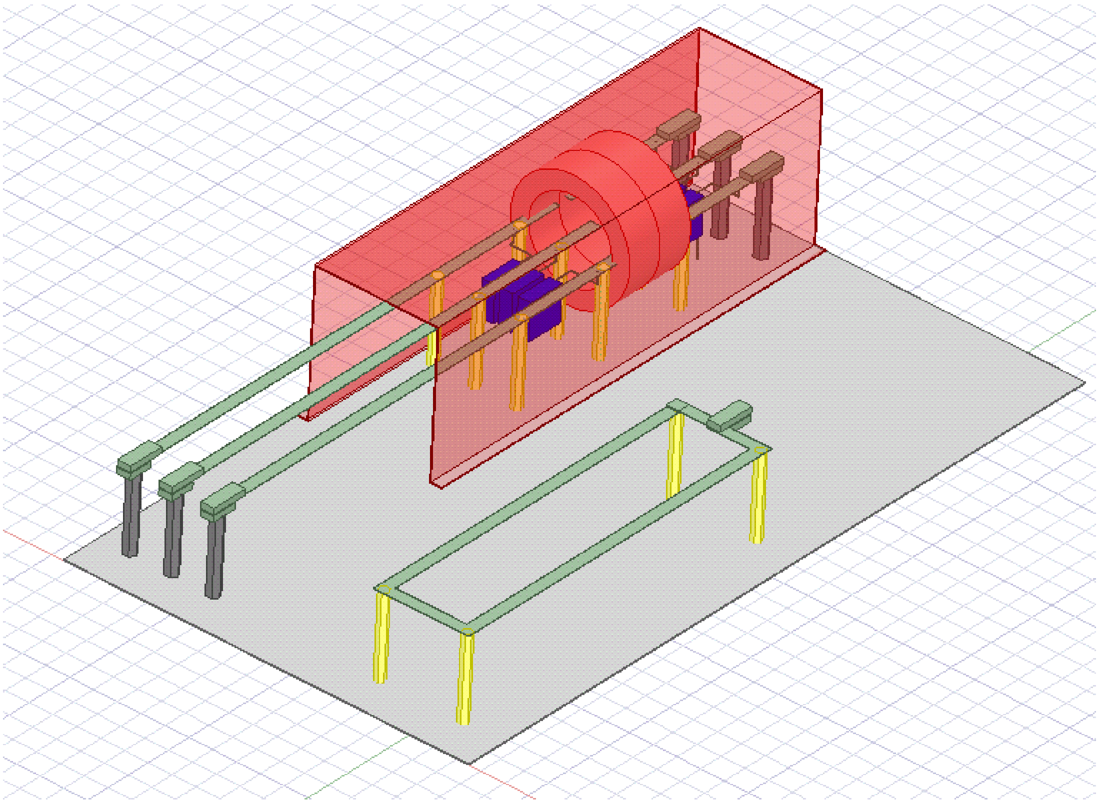

Figure 43. *The shielded EMI filter*

The used shield was the same 1 mm thick aluminium shield that was used in the section 4.3.1. The results are presented in the figure 44.

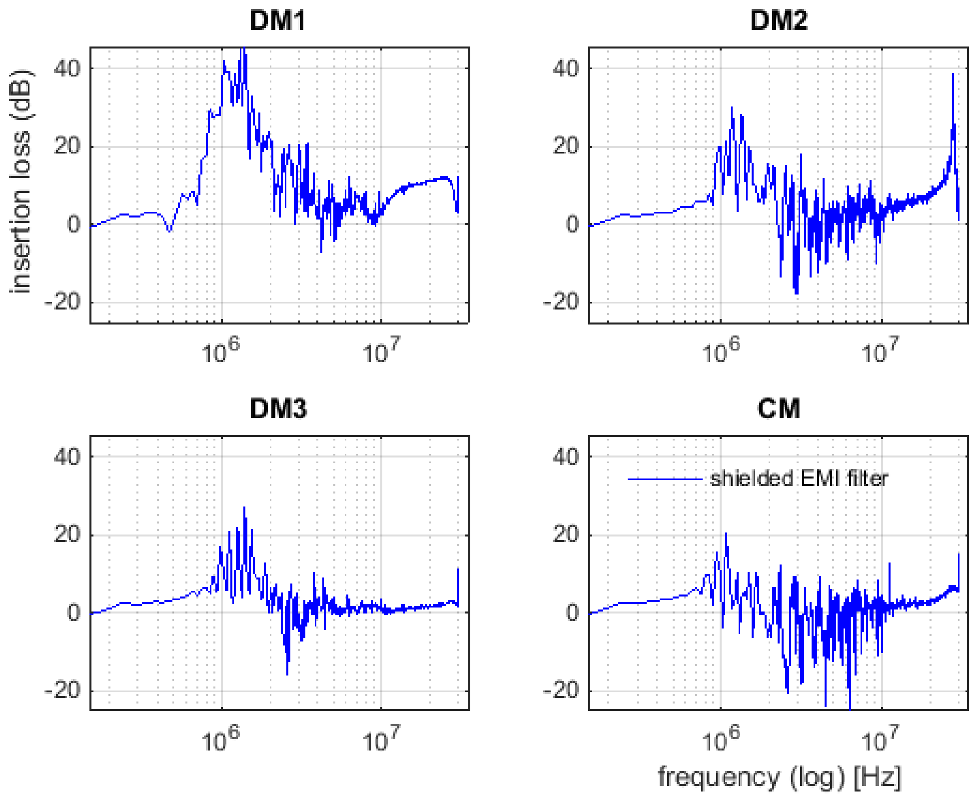

Figure 44. *Measured insertion loss with shielded EMI filter compared to the reference set-up*

As seen in the results, the shield over an EMI filter has only minimal effect to coupling. The difference to non-shielded set-up is about 3 dB. However, the capacitors at the grid connection were not removed and a low impedance path for differential noise is provided that way. This might hide the effect of the EMI filter shielding. The measurement results are noisy due to relative low measured signal strength.

4.5 Solution for an existing drive

To validate results of the research done with simplified model the more cost effective solution to fulfil C2 EMC-level were designed to an existing drive. Former solution were to compensate an EMI coupling with many filter components so the savings would be achieved when the number of those can be reduced after EMI coupling prevention. Connector positioning solutions cannot be implemented to existing drive so the solutions bases on shielding and EMI filter design.

An idea was to build an EMI-filter and the grid connection of a drive close to a metal plate which can be effectively shielded. The grid side capacitors of the EMI filter were removed and differential inductance were added with two N87 material ferrite cores and two piercings in a common-mode filter. The implemented solution on the grid connection area is presented in the figure 45.

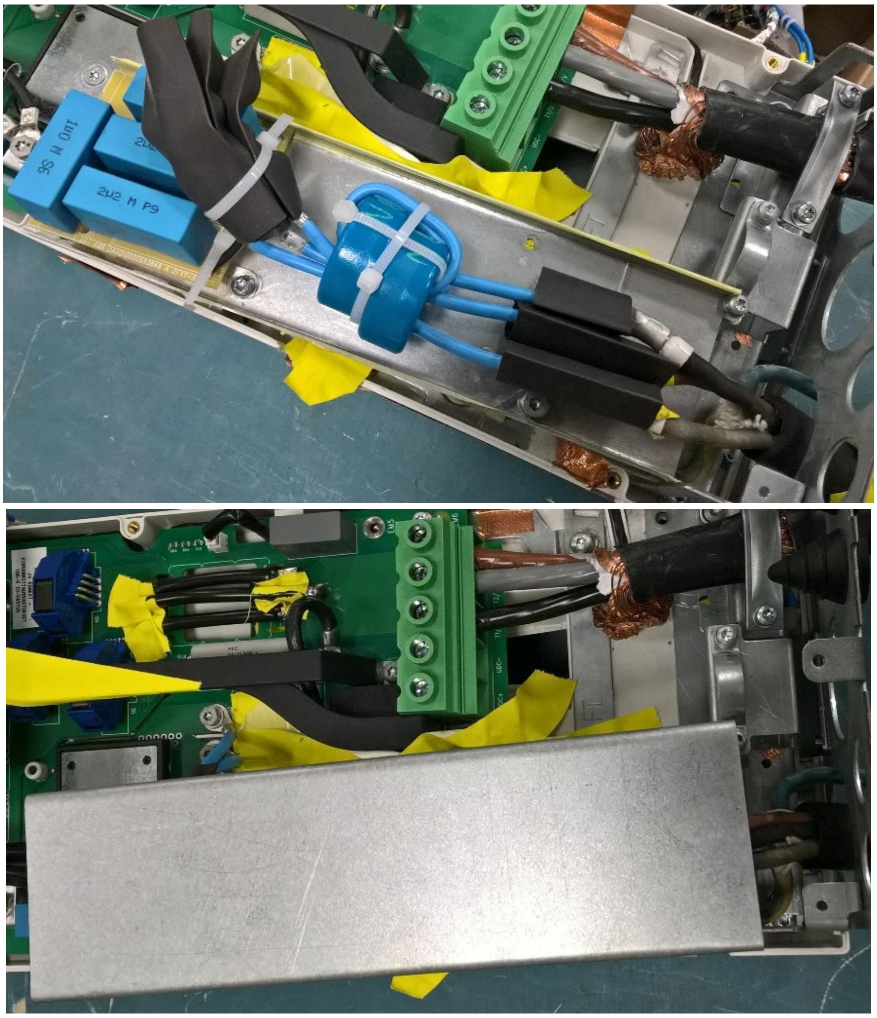

Figure 45. *The implemented grid connection area to prevent EMI coupling with bottom plate and the shield*

The former solution contained nine ferrites and seven capacitors. The proposed solution has only two ferrites and four capacitors. The solution was tested in the standardized conducted emissions test as described in the section 3.3.2. The test was conducted without any shield, with metal plate on bottom and with the complete shield. Results are presented in the figure 46.

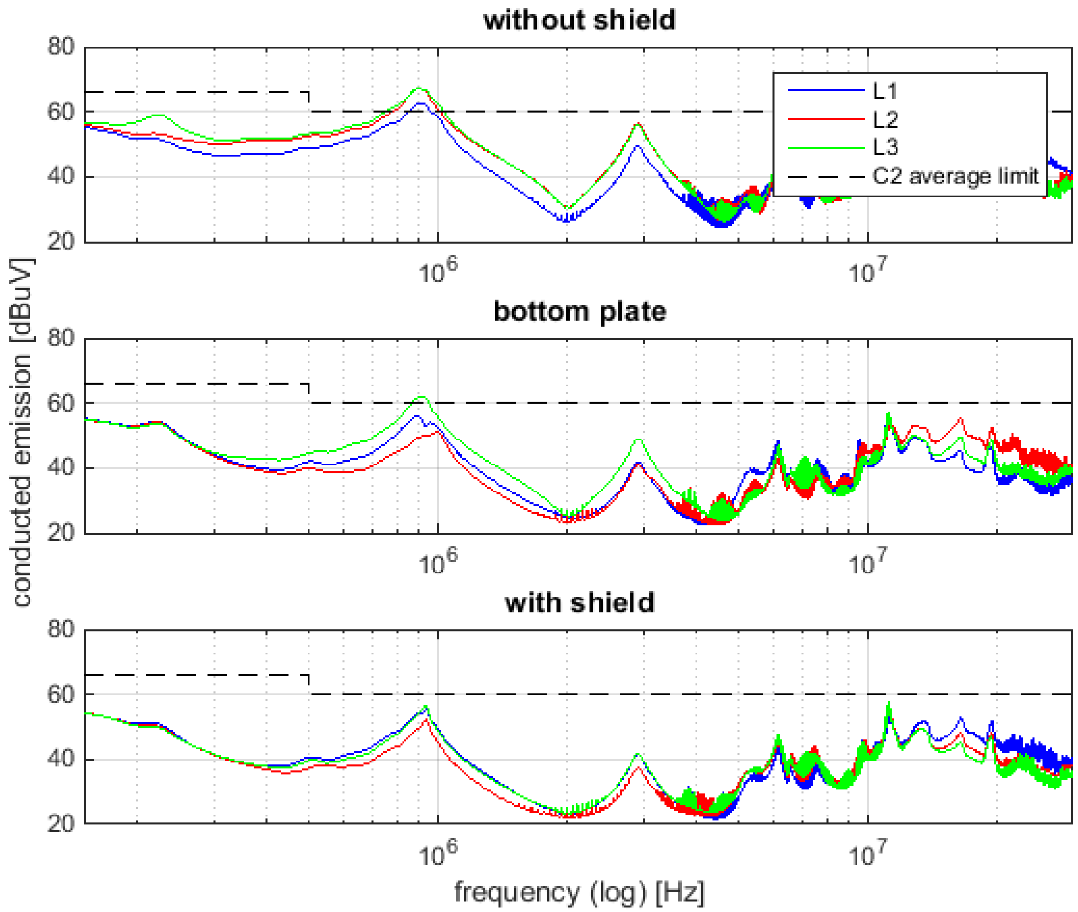

Figure 46. *Average conducted emissions of the tested drive without and with the different shields*

As seen in the figure, the tested prototype drive do not fulfil C2 EMC limits without the shield. The coupling can be seen from the imbalanced results in different phases around 1 MHz frequency. The phase L3 is the closest to the motor connection and have therefore highest result. The bottom plate seems to be effective but the L3 phase is still over limit. The complete shield removes imbalance almost completely and the tested drive fulfils C2 limit with it.

4.6 Feasibility and cost effect of the improvements

Proposed solutions for new and existing drives should be feasible to implement to drive regarding the standards, common product requirements and other components of the drive. The solutions should also have positive cost effect to drive design. Feasibility and cost effect of the each previously presented solution category is discussed generally. Only effective solutions are discussed. Solutions for existing drives are investigated more detail due to better available information.

Connector positioning solutions cannot be implemented to existing drives because placement of the connectors cannot be moved. In a new drive design the effective solution of the level difference is easily implemented by layout design. Its cost is therefore a zero. The angular difference is very effective solution but it is doubtful that it could be implemented to real drive because it requires precise actions from the drive assembler. It can be claimed as a non-feasible solution.

The shielding was shown to be very effective solution and use of the shield in a drive is therefore very recommendable. Adding a shield to a drive needs a small modifications to the layout but can often be implemented to the same amount of space than a previous EMI filter. The use of the shield have often a positive cost effect because the number of the filter components can be reduced and a steel is a relative cheap material.

The modifications to the EMI filter topology are easiest to implement of the all investigated solutions. In most cases the implementation can be done by component changes. The removing the useless components and using cheaper materials in the cores of the chokes has always a positive cost effect.

The solution implemented to an existing drive showed how feasible and cost effective the actual solution can be. The solution was implemented to the same space than the previous EMI filter and an input filter that was not mounted to the printed circuit board was also removed due to need for less components. The cost-effect to the EMI filter material costs is positive with estimated component prices. Estimation was based on the volume prices of the similar components. The estimated calculation is presented in the table 3.

	bottom plate	**full shield**
component costs	-62 %	-62 %
shield cost	25 %	50 %
cost effect	**-37 %**	**-12 %**

Table 3. *The estimated cost effect to the EMI filter of a drive*

The reduction of the over half of the components reduces component costs of the EMI filter by 62 percent. Depending the needed solution to fulfil desired EMC limit, the achieved cost reduction is from 12 to 37 percent.

5. RESULTS

In this part the most important results of the different solutions to reduce an EMI noise coupling in a two-level AC drive are discussed. Results based on simulations and measurements conducted in the part 4.

5.1 Connector positioning

The effect of the connector positioning to the EMI coupling was investigated in the chapter 4.2. The measurement results were traces that represent a difference in an insertion loss as a function of the frequency. The each measurement produces four traces which represents the differential signal in phases L1, L2 and L3 and in a common-mode noise CM. To represent results together the difference in the insertion loss compared to the reference situation at the 1 MHz frequency are collected to a table. Simulated results are presented as a grey and measured results as a black in the table 4. Good results are presented with green and poor results with red colour.

Table 4. *Results of the connector positioning measurements*

Set-up	L1 sim	L1 meas	L2 sim	L2 meas	L3 sim	L3 meas	CM sim	CM meas
Vertical difference -5 cm	5,9	5,5	1,9	3,3	6,7	5,1	7,3	6,8
Vertical difference +5 cm	-0,4	0,6	-1,4	4,2	-0,2	1,2	-0,6	-0,4
Vertical difference +10 cm	3,5	4,5	6,2	8,2	3,1	6,5	1,8	2,5
Horizontal difference +10 cm	0,9	1,2	-1,8	1,7	1,4	1,2	1,9	1,2
Horizontal difference +20 cm	7,4	6,2	5,7	7,2	7,6	6,3	6,7	6,6
Combined –5 cm vertical and +20 cm horizontal difference	14,2	11,6	17,0	14,6	13,8	12,6	13,7	12,2
Angular difference 35 degrees	11,7	12,9	5,7	9,8	13,0	12,0	-2,2	-2,4

Overall simulations and measurements followed each other's well. Therefore the results are discussed generally based on different solutions. The effective solutions differentiated clearly.

The solutions which have not significant effect were 5 cm positive vertical difference and 10 cm horizontal difference. 5 cm positive vertical difference causes a larger loop between a ground plate and conductor which generates more a common-mode noise. The 10 cm horizontal difference is a relative small change with 30 cm long cables and therefore its effect is small.

5 cm negative vertical difference, 20 cm horizontal difference and 35 degrees angular difference were all clearly effective solutions. So was 10 cm positive vertical difference but it is not discussed more because the 5 cm negative difference was more effective. The

horizontal difference decreased an EMI noise in all phases similarly. 5 cm negative vertical difference reduced a common-mode noise more than a differential noise and the angular difference has an opposite effect. The common-mode noise was actually higher than in the reference situation.

Based on the results of the 5 cm positive and negative height difference can be said that phase conductors distance to a ground plate is more important than actual height difference. Distance to ground plate should be minimized to reduce coupling.

The vertical and horizontal differences can be implemented in a same device so their cooperative action were interesting to investigate. The result was that combining different solutions seems to be effective and the combined result can be calculated from individual results with a decent accuracy. The most effective solution was to combine solutions.

5.2 EMC Shielding

Shielding appeared to be very effective solution to reduce coupling between grid and motor connections. The results of the research done about EMC-shielding in the chapter 4.3 are presented at the similar table than the positioning measurements results at the previous section. However, the simulation results were not used and there are measured insertion loss compared to the reference set-up at the 1 MHz frequency with aluminium and with steel presented in the table 5. The steel results are presented as a grey and the aluminium results as a black. Good results are presented with green and poor results with red colour.

Table 5. *The results table of the EMC shielding research*

Solution	DM1 Fe	DM1 Al	DM2 Fe	DM2 Al	DM3 Fe	DM3 Al	CM Fe	CM Al
Shield on a grid connection	16,4	24,9	28,9	24,9	19,3	29,9	17,3	26,0
Shield on a motor connection	30,4	35,5	24,8	23,4	36,6	35,8	37,9	37,1
Shield on both connections	41,7	35,7	27,2	25,8	43,7	36,4	45,7	44,6
Closed ends shield on a grid connection	na	24,8	na	22,7		28,2	na	29,3
Steel net shield on a grid connection	18,3	na	21,9	na	19,4	na	21,7	na
Shorted turn shield on a motor connection	5,8	na	8,5	na	5,9	na	5,2	na

The investigated shield materials were both feasible for investigated use. It seems that aluminium can be slightly better on a grid connection and steel on a motor connection but that cannot be justified by just one sample.

The shielding the both connections was the most effective shielding and shielding the motor connection was a bit more effective than shielding the grid connection. However, there is also other noise sources in a drive so the shield on the grid connection may often be better to choose. If the heat is a problem in the drive, the grid shield is also effective but not as effective as the plate shield. The shorted turn shield is proposed to be used only when other options are not possible.

The small apertures seems not to decrease shielding effectiveness and that makes design of the shield relative easy in drives. The shield can be open from the input and output sides of the cables. Because of the relative high shielded frequencies, the use special magnetic materials is not needed and steel or aluminium are recommendable materials.

The simulation results were inaccurate compared to the measurement results as it was expected. The shielding effect that Q3D simulates is only directional and because it is not understood the Q3D should not be used to design shields.

5.3 EMI filter topology

Based on the simulations and measurements done in the chapter 4.5 it is shown that EMI filter topology have an effect to a coupling between drive connections. The simulated and measured insertion losses with different solutions at 1 MHz frequency is presented in the table 6. The more effective results are presented with green and less effective with red colour. The effect of the differential inductance was only simulated.

Table 6. *The results table of the different EMI filter topologies*

Set-up	DM1 sim	DM1 meas	DM2 sim	DM2 meas	DM3 sim	DM3 meas	CM sim	CM meas
Additional CM filter to the grid connection	0,3	na	0,1	na	-0,4	na	5,4	na
10 uF differential inductance to the grid connection	6,4	na	6,6	na	5,9	na	-0,2	na
Grid side capacitors moved close to the grid's end of the model	11,0	16,2	8,6	8,2	11,7	11,7	0,00	4,1
Grid side capacitors removed	-0,2	3,1	0,5	1,2	-0,3	0,4	-0,2	-0,7
EMI filter shielded	2,0	5,1	1,8	3,1	1,9	0,9	3,0	2,2

The results shown that the coupling is effectively damped if the grid side capacitors of the EMI filter can be placed close to the grid connection. This action minimize a differential loop where EMI noise can induce. In most drives it is not possible due to standardized space needed for assembly of the grid cable in the conduit box of a drive. In that case removing the grid side capacitors is recommendable because it removes a differential loop without differential inductance from the drive connections. The removing of the capacitors does not decrease the insertion loss even when the differential inductance is very low as it was in the simplified model. If the common mode choke have the higher differential inductance the removing of the capacitors would be very beneficial.

Increasing the differential inductance of the grid connection has always a positive effect as seen in the results of the added 10 μF inductance. The differential inductance can be added by increasing the leakage inductance of the common mode choke. This can be done by using low permeable materials such as ferrites as a core of the choke. The tested high permeable materials do not have a wanted effect as seen from the results of the additional common mode choke. The differential inductance can also be added with additional turns on the choke if the increased heat is not a problem. The proposed EMI-filter topology is presented in the figure 47.

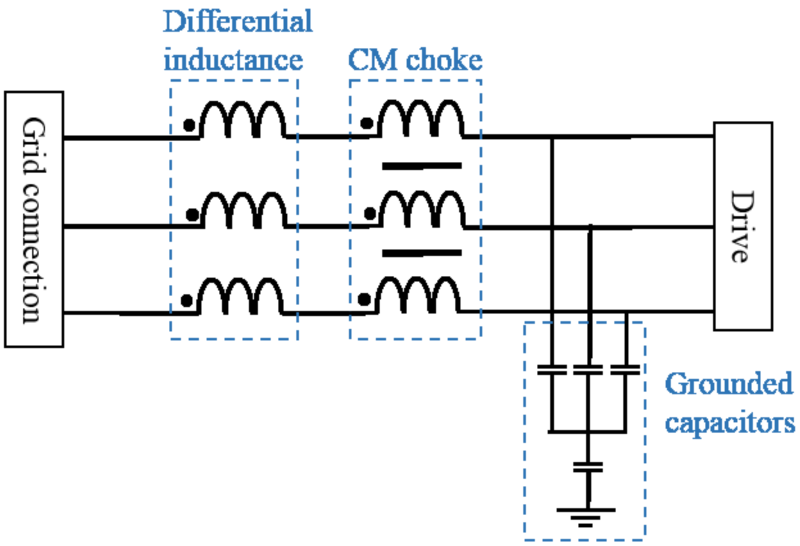

Figure 47. *The proposed EMI-filter topology*

The shielding of the EMI filter seems not to be very effective with 3 dB damping compared to the 20 dB damping of the shield on the grid connection conductors. However, the results of this set-up were noisy and in this test the grid connection were not shielded. Together with grid side capacitors, the non-shielded low impedance differential loop is formed and the effect of the shield is probably overwhelmed by this. The EMI filter shield is therefore not completely investigated. It is proposed to shield EMI-filter also until the more research about most critical components to be shielded is done. The EMI-filter is shielded also in the tests with a drive in the chapter 4.5.

5.4 Solutions for existing drive

The proposed solution was shown to be effective to damp coupling between grid and motor connections of a drive. The measured effect of the bottom plate shield with differential inductance added by two piercings in a common mode filter was significant and it may be used in the most cases alone. The full shield prevented coupling almost completely and should be used when the bottom plate is not enough to fulfil desired EMC limit.

The proposed solution reduced the number of the components of the EMI filter significantly which makes possible to implement the shielded filter to the same space than the previous filter. By optimizing the rest of the drive's EMC related components and EMI grounding points with the assembled filter the results can maybe still improved.

5.5 Feasibility and cost-effect of the improvements

The most of the proposed solutions were feasible to implement for a new drive design. The angular difference was stated to be non-feasible due to the difficult assembly. The filter topology changes were easiest to implement for existing drives and is therefore the first option if the coupling is problem in already designed drive. The shield can often implemented without changes to the drive frame and should be considered at least in the new drive design due to its effectiveness to damp the coupling between connections.

The connector positioning and the EMI filter topology solutions have always a positive or zero cost effect and can therefore implemented always when needed. If the shield is needed the cost of the shield makes estimation a bit more difficult. However, with estimated component prices the shield provides at least 12 percent saving in the component costs of the EMI filter. This is due to significant reduction in amount of the filter components.

6. CONCLUSION

EMI coupling between grid and motor connections of a drive is phenomena where EMI noise from the motor connection is induced to the grid connection when connections are placed close to each other. The main coupling method is an inductive coupling between phase conductors of motor and grid cables that are opened to the drive connectors. This coupling bypasses an EMI filter which is designed to keep EMI noise at the motor side of the drive. EMI noise in the grid connection worsen the results in the conducted EMI EMC test which the drive has to pass to be sold on European markets.

The goal of this research was to provide design guidelines to reduce EMI coupling between motor and grid connections of a drive. With these guidelines the drive should fulfil the C2 limits of the conducted EMI test standardized in IEC 61800-03. Possible solutions were designed based on the theories of a coupling, an EMI generation, filters and a drive. These solutions were then tested with simulations and measurements with simplified model of the drive connection environment. Finally the proposed concept was tested with the drive in standardized EMC tests. The feasibility and a cost-effect of the solutions were also discussed.

There was not previous research available about couplings between connections of a drive. Therefore the proposed solutions were based on coupling reduction methods that were used in similar problems in other applications. Also a basic theories of the different coupling methods were discussed to find out if there are some drive specific coupling issues. Three different solution categories were identified which were then investigated in detail. These categories were change placement of the connections of the drive, shield the drive connections and design the EMI filter topology so that it reduces the EMI coupling.

The placing coupled connections away from the each other is an obvious solution to reduce coupling but the product requirements demands that connections are placed side by side on the same end of a drive. However, this allows to place connectors with horizontal difference. This reduces the coupling quadratic to the distance between connections and is proposed to be used when possible regarding the space limitations in the drive. The vertical difference was also investigated but it was more important to place both connections close to the grounded chassis of the drive than have vertical difference between connections. It is proposed to discuss if the connections can be placed away from the each other in the future drive concepts. That would be the most cost-effective way to reduce the coupling.

An absorption loss was identified to be the most important shielding technique with the investigated frequencies from 150 kHz to 30 Mhz. The materials that are easily available and have a good conductivity like a steel and an aluminium were proposed to be used as a shield. The both materials seemed to be effective and the shielding was the most effective of the feasible solutions to reduce coupling. It is likely that number and size of the filter components can be reduced when the shield is used which cause savings with material costs. The insertion loss of the shield on the grid connection was 20 dB. Because shield causes extra costs, it is proposed to test at first if a drive pass a conducted EMI test with only shield plate under the grid connection. Its effect was also significant and it is more cost effective than the complete shield. The net shield can be used if it is needed because of the heat. It is as effective as the plate shield.

The topology of an EMI filter is proposed to be considered also from an EMI coupling point of view during design. The topology should have some differential inductance at a grid connection. The simulated result was that 10 µH is enough. Therefore the grid side capacitors of the EMI filter is recommend to be removed and differential leakage inductance of a common mode choke of the EMI filter increased. It can be done by an extra piercing or with a less permeable core material. If the extra piercing is used, the more heat is generated in a drive and the core of the common mode choke saturates more easily.

The test with a prototype drive proved that proposed solutions can be implemented to a drive and that those are effective. The C2 limit was fulfilled with about 60 percent less components than with the ordinary solutions. The estimated saving in material cost of the filter is from 12 to 37 percent depending the needed shield. The tested solution for the prototype drive can easily be duplicated to other drive models also.

The possible future research topic would be to optimize proposed solution. For example how a shield should be grounded so that it forms a minimum loop with the grounded chassis of the drive and what would be an optimal values for the EMI filter components regarding the coupling. The magnetic behaviour of the shield materials with higher frequencies was also topic which can be researched more.

This study provided a feasible solution to reduce EMI coupling in a drive connections with a cost effective way. The proposed design guidelines would make also design process quicker when try and error method is replaced with a holistic view to the topic. This is the way how EMC topics are hopefully solved in the future.

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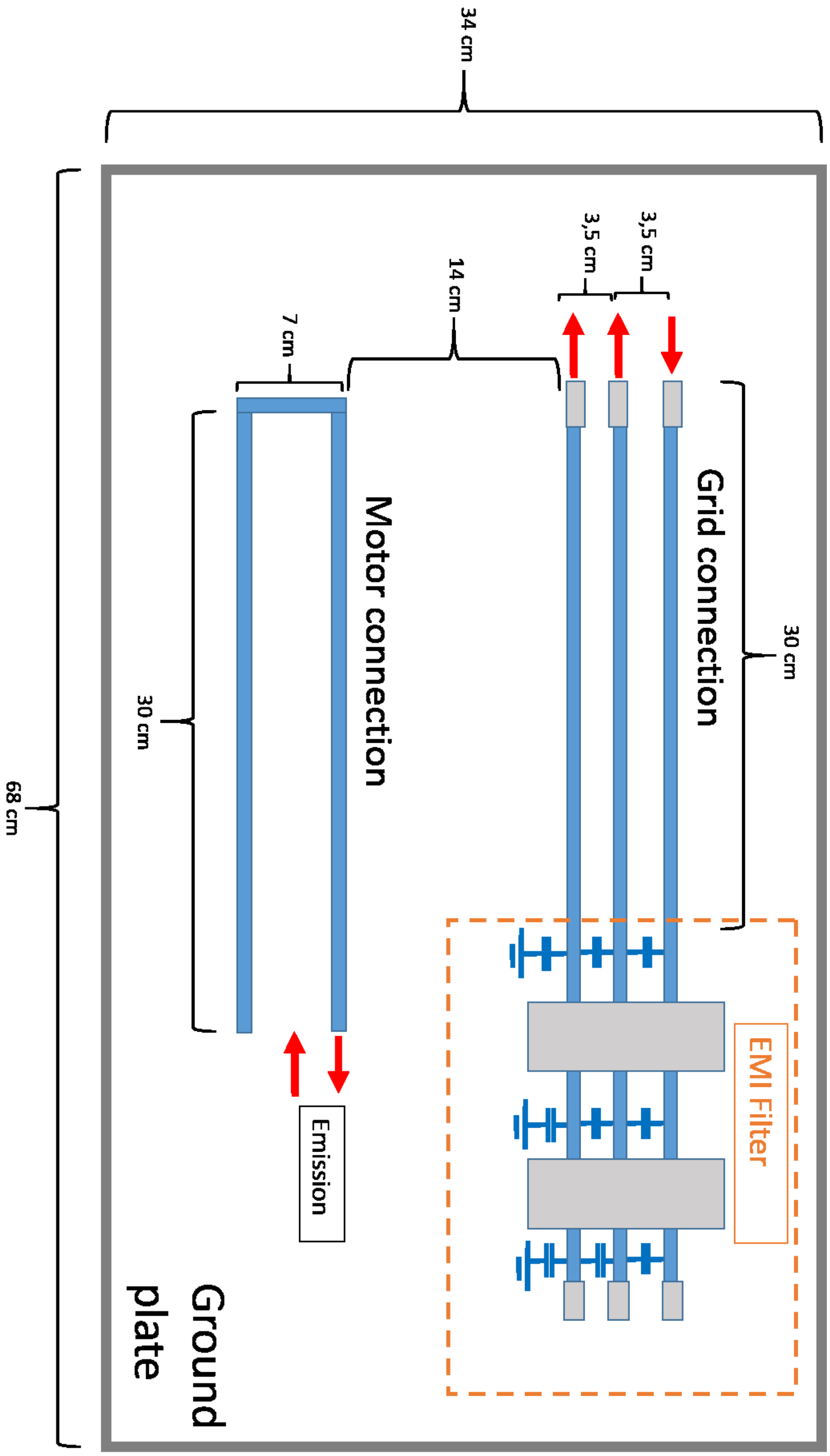
APPENDIX A: DIMENSIONS OF THE SIMPLIFIED MEASUREMENT MODEL



APPENDIX B: SIMETRIX SIMULATION MODEL OF THE SIMPLIFIED MEASUREMENT MODEL